July-August, 1965

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LUBRICATION ENGINEERING

RESEARCH APPLICATION EDUCATION MAINTENANCE

Vol. 11, No. 4 July-August, 1955

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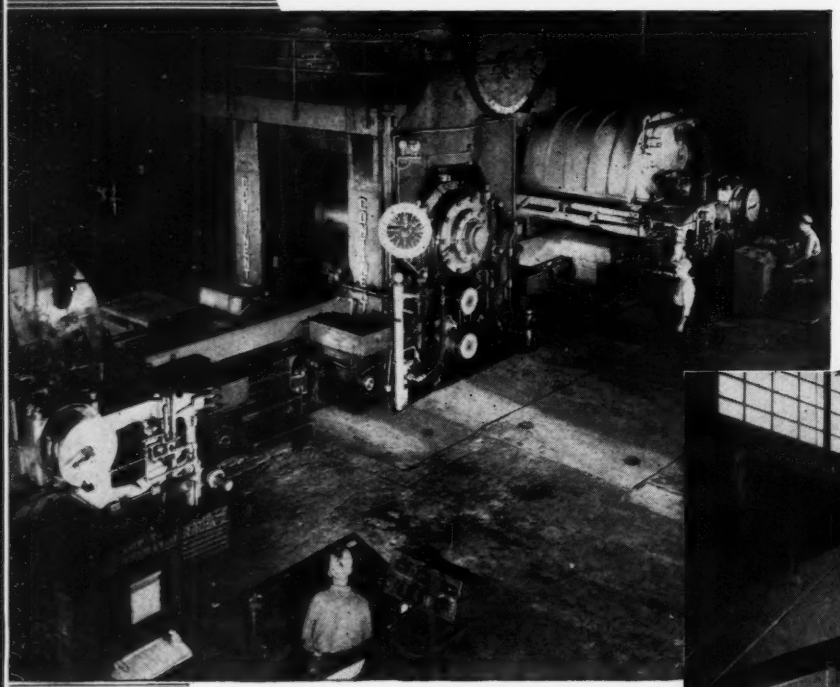

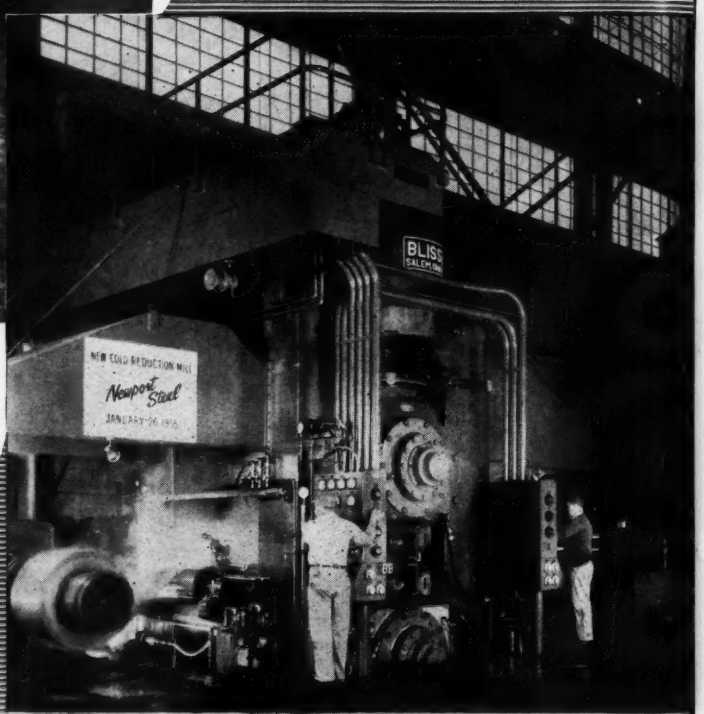

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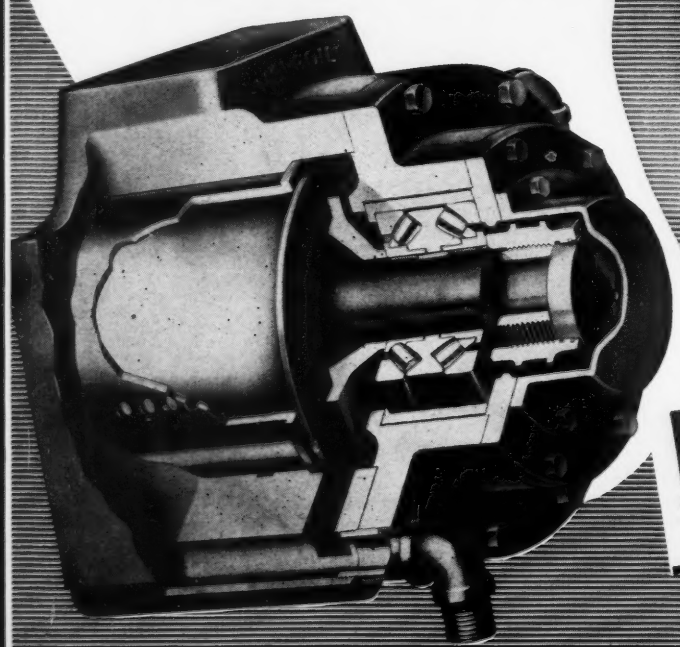

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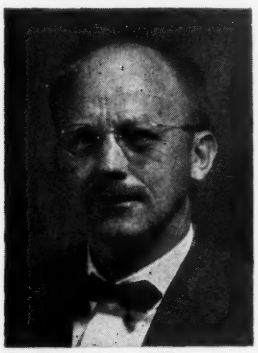
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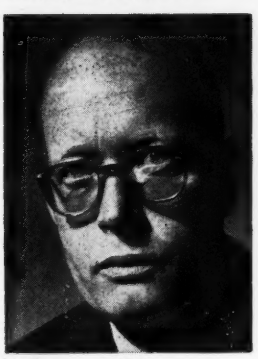
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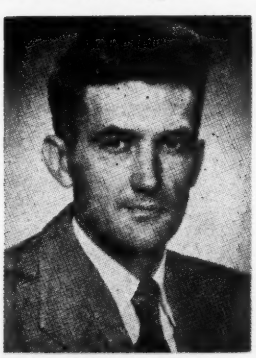
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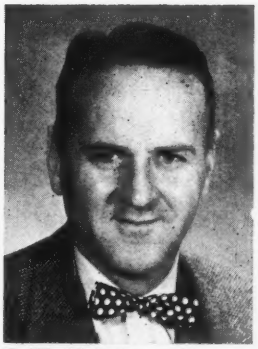
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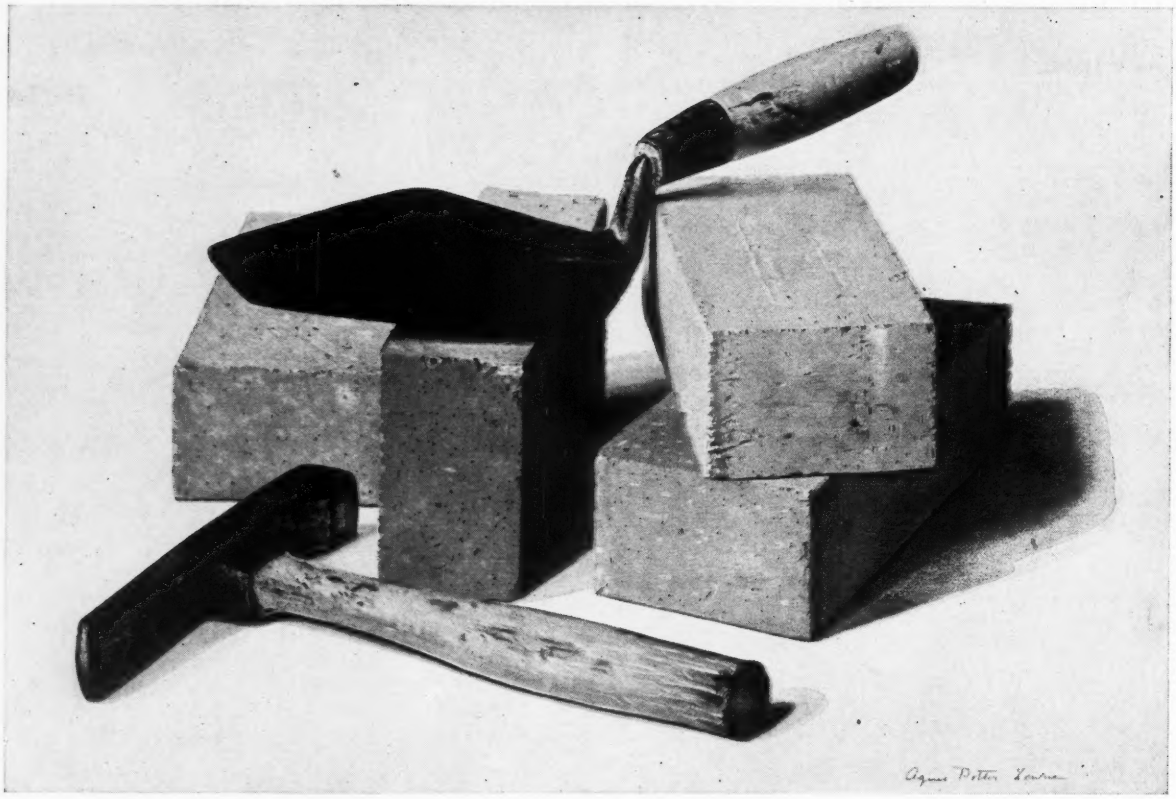

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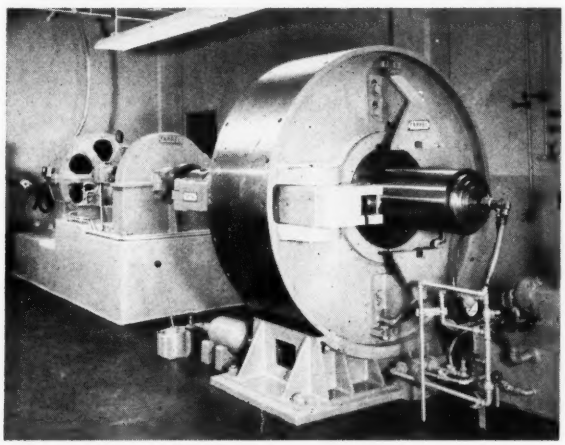

Testing Machine For Large Plain Bearings. A new bearing testing machine has recently been installed in the laboratory of Farrel-Birmingham Co., Inc., Ansonia, Conn., designed for full-scale testing of large plain bearings under conditions simulating as nearly as possible those used in such industrial equipment as Banbury mixers, rubber and plastics mills and calenders, rolling mills, and sugar mills. Tests will be run on a variety of plain bearing liners such as bronze, babbitt, and aluminum. Journals will be of both steel and cast iron. Effect of speed, surface finish, journal temperature, and oil viscosity will be observed. The machine has a basic journal size of 14" diameter (shown in photo with test bearing removed). A maximum load on the bearing of 300,000 pounds can be exerted, as produced through an hydraulically actuated lever system with actual force measured by strain gauge. Main framework of machine is made as a circular ring so that frame can be rotated to apply load horizontally as shown or from above or below as desired. The driving means for the rotating journal includes a torque meter for measurement of friction torque. Thermocouples are placed in bearing liners to record bearing temperature during operation of tests. Test bearings are lubricated with the several types of lubrication systems that are used in actual commercial operation. Provision is made for heating the test journal to simulate operating conditions encountered in plastic mills and calenders.

Reduction In Occurrence Of Freight Car Hot Boxes. A significant reduction in the occurrence of freight car hot boxes ultimately may result from findings of the comprehensive research project by Armour Research Foundation of the Illinois Institute of Technology for the Association of American Railroads. George L. Pigman (who supervised the

(Continued on Page 283)

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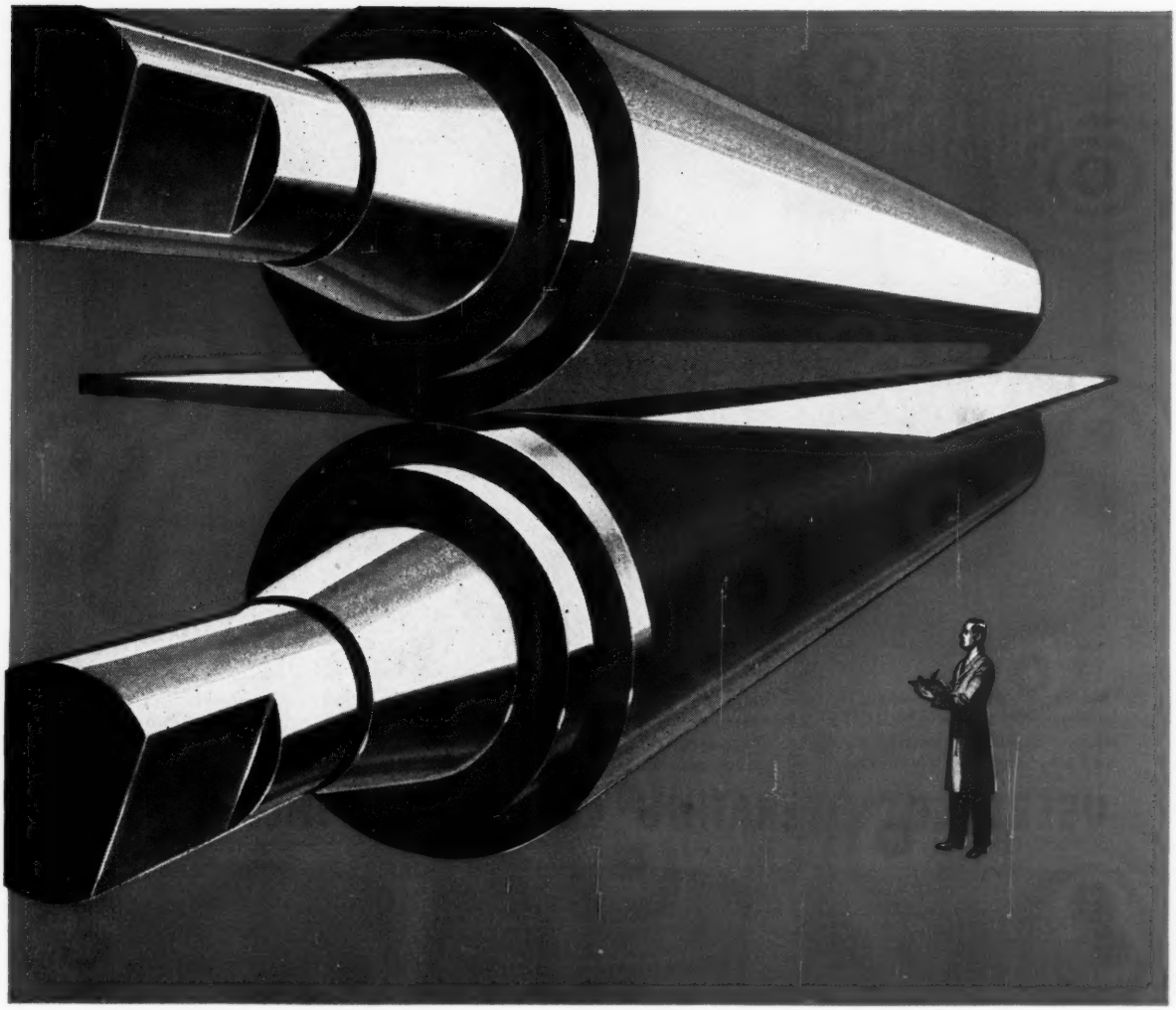

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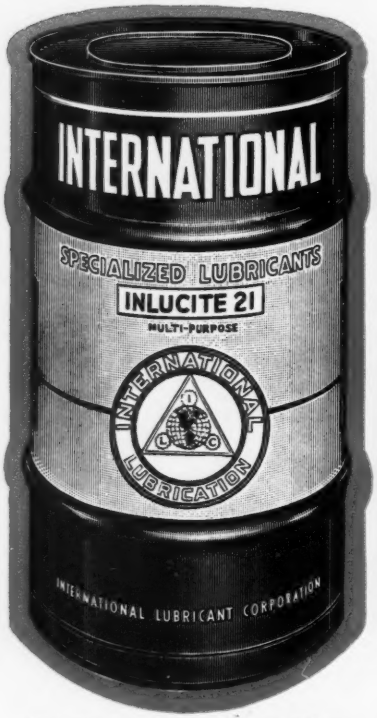

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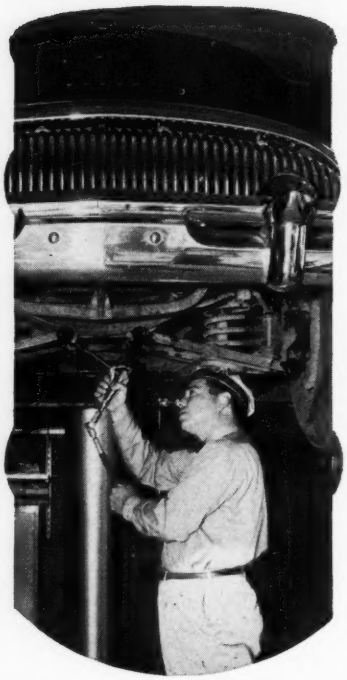

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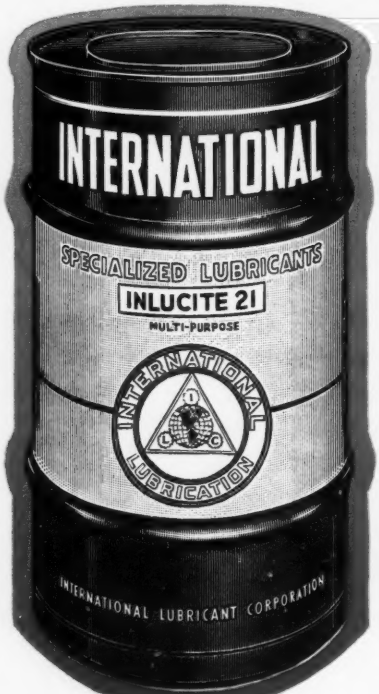

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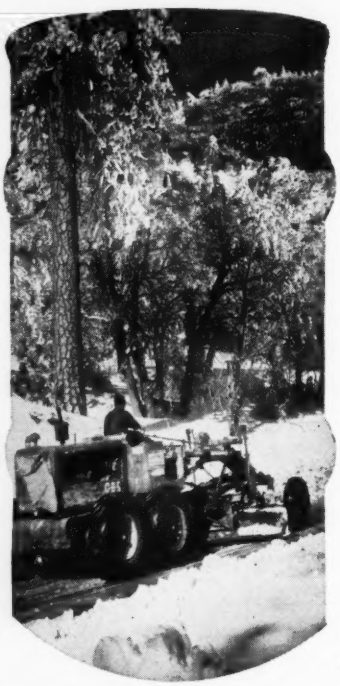

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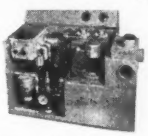

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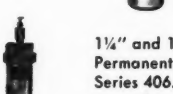
Replaceable, transparent oil reservoir.
Reversible. Series O-40.



¼" pipe size.
Permanent, metal oil reservoir.
Model 399-2.

½ PT. OIL CAPACITY

5 pipe sizes, ¼" to 1" inclusive.
Replaceable, transparent oil reservoir.
Reversible.
Series O-41 and O-42.

5 pipe sizes, ¼" to 1" inclusive.
Replaceable, metal oil reservoir.
Reversible.
Series SO-41 and SO-42.

1 QT. OIL CAPACITY

5 pipe sizes, ¼" to 1" inclusive.
Replaceable, metal oil reservoir.
Reversible.
Series S406.

1¼" and 1½" pipe sizes.
Permanent, metal oil reservoir.
Series 406.

2 QT. OIL CAPACITY

5 pipe sizes, ½" to 1½" inclusive.
Permanent, metal oil reservoir.
Series 408.

2 GAL. OIL CAPACITY

5 pipe sizes, ¼" to 1" inclusive.
Replaceable, metal oil reservoir.
Reversible.
Series X400 and X402.

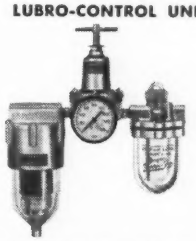
1¼" and 1½" pipe sizes.
Replaceable, metal oil reservoir.
Series X406.

5 GAL. OIL CAPACITY

5 pipe sizes, ¼" to 1" inclusive.
Replaceable, metal oil reservoir.
Reversible.
Series Y400 and Y402.

1¼" and 1½" pipe sizes.
Replaceable, metal oil reservoir.
Series Y408.

LUBRO-CONTROL UNIT



showing typical combination of Micro-Fog Lubricator with Automatic-Drain Filter and Air-Pressure Regulator.

OVER 1,100,000 NORGREN LUBRICATORS PUT TO USE IN INDUSTRY

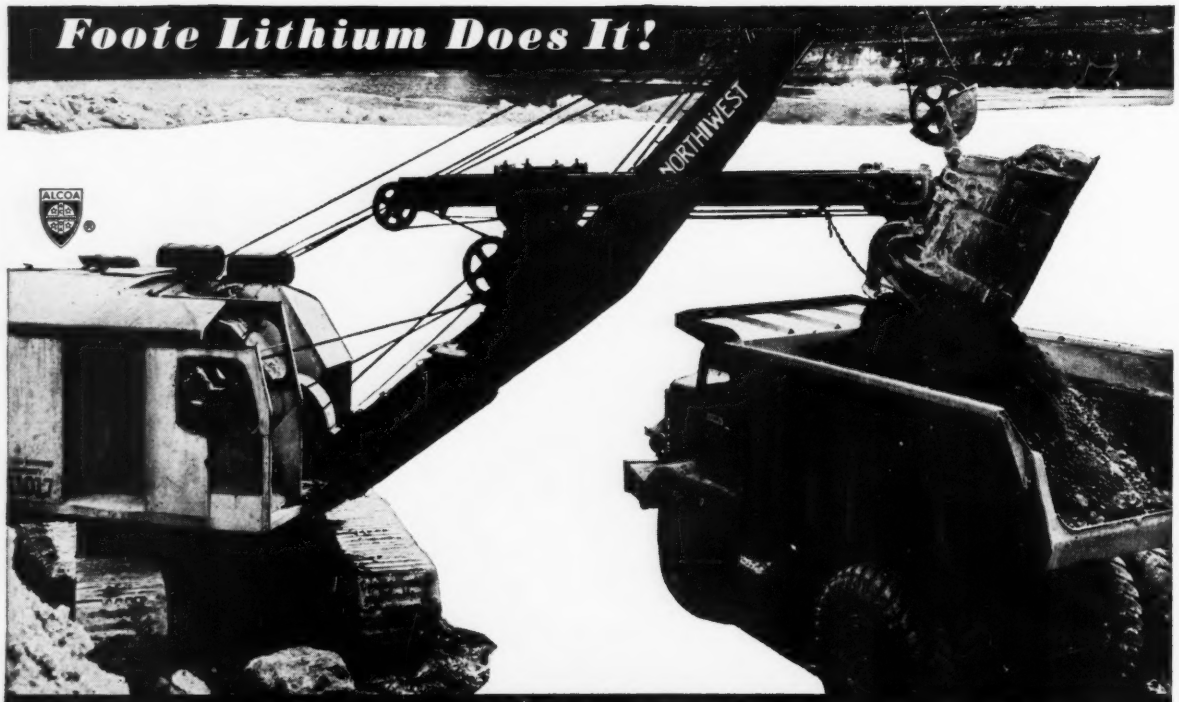
C. A. Norgren CO.
3434 So. Elati, Englewood, Colo.

Phone the Norgren representative listed in telephone directory classified section under "Norgren Pneumatic Products"... or

WRITE FOR CATALOG →

showing latest developments in Micro-Fog lubrication and giving data on Norgren's *complete line* of lubricators, air filters, pressure regulators, valves, hose assemblies.

Foote Lithium Does It!

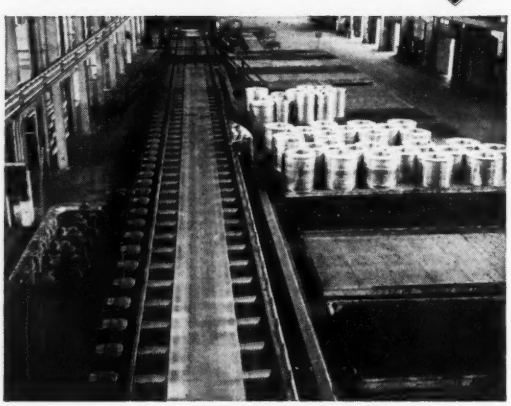


A MULTI-PURPOSE GREASE REPLACES OVER 15 LUBRICANTS at ALCOA

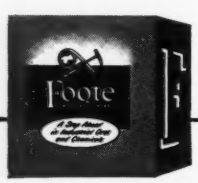
From all-weather lubrication of mining equipment to keeping massive "run-out" tables rolling smoothly, the Aluminum Company of America uses a multi-purpose grease for lubricating critical bearings of many types and sizes. In fact, this one multi-purpose grease has replaced over 15 special types and grades of grease.

Result—Simplified inventory. Correct lubrication is assured, because this multi-purpose grease lubricates effectively at temperatures ranging from —50°F to over 350°F . . . in wet or dry conditions . . . continuous or intermittent operations.

These benefits can be yours. It will pay you to get full details on lithium base, multi-purpose grease from your grease supplier.



We will be glad to send you a copy of "Front Wheel Bearing Lubrication," an N.L.G.I. report.



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FOOTE MINERAL COMPANY
447 Eighteen West Chelten Building, Philadelphia 44, Pa.
RESEARCH LABORATORIES: Berwyn, Pa. • PLANTS: Exton, Pa.; Kings Mountain, N.C.; Sunbright, Va.

KLOZURE* OIL SEALS

protect the pitch bearings on Piasecki's newest helicopters

KLOZURE Finger Spring Model 53 with silicone sealing element and felt washer.

In designing the pitch bearing assembly of the new H-21 cargo and troop transport helicopter, Piasecki engineers needed a dependable oil seal which would protect the needle bearings in this assembly under the most severe flight conditions . . . at temperatures ranging from −65°F. to +160°F.

After exhaustive tests, Piasecki engineers selected our finger spring KLOZURE Model 53 with silicone sealing element and felt washer. This superior oil seal gave *positive* bearing protection under *all* operating conditions—dust and contaminants were sealed out, the lubricant was sealed in.

Let us show you how Garlock KLOZURES can solve your sealing problems. There's a proven KLOZURE model for every bearing application. For complete information, contact the Garlock office nearest you or write for KLOZURE Catalog 10.

THE GARLOCK PACKING COMPANY, PALMYRA, N. Y.

Sales Offices and Warehouses: Baltimore • Birmingham • Boston • Buffalo • Chicago Cincinnati • Cleveland • Denver • Detroit • Houston • Los Angeles • New Orleans • New York City • Palmyra (N.Y.) • Philadelphia • Pittsburgh • Portland (Oregon) • Salt Lake City • San Francisco • St. Louis • Seattle • Spokane • Tulsa.

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GARLOCK

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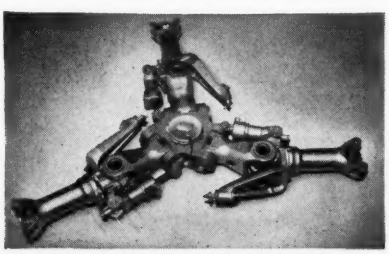
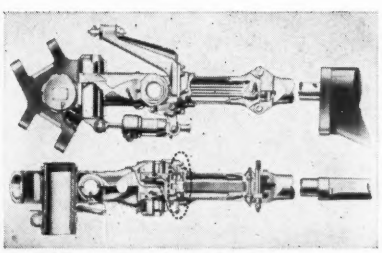
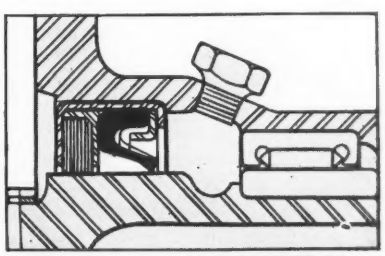


Complete rotor hub assembly for H-21 helicopter showing 3 pitch housing assemblies.



Pitch housing assembly cut-away to show pitch shaft and bearing assembly.



Installation of Model 53 KLOZURE Oil Seal on the pitch shaft needle bearing.

79 YEARS of Lubrication Service to Industry

Brooks lubrication engineering—constant research in the laboratory and "on the job" has been devoted exclusively to the development of industrial lubricants. The wealth of experience and knowledge gained through solving the "tough" lubrication jobs of industry during the past seventy-nine years has resulted in a dependable extreme pressure lead base compound known throughout industry as "Leadolene Klingfast." Hundreds of case studies prove that it lowers lubrication costs and increases service life of equipment. We suggest you try it for trouble-free, economical lubrication of the following:

OPEN GEARS • SCREW DOWNS
MILL TABLES • WIRE ROPE • MILL PINIONS
HIGH TEMPERATURE LUBRICATION
HYDRAULIC SYSTEMS • CIRCULATING OIL SYSTEMS • FLEXIBLE COUPLINGS
WORM DRIVES • ROLLER BEARINGS
ENCLOSED GEARS AND BEARINGS

BROOKS

LEADOLENE

Klingfast

Write for your copy of "The Brooks Oil Story!"

The Brooks Oil Company

Since 1876

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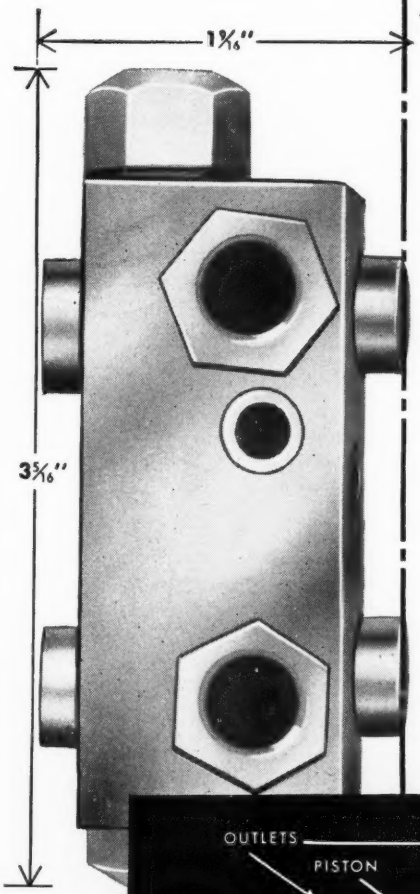
Characteristics of LEADOLENE KLINGFAST

pH-ilm Strength . . . 50,000 psi minimum.
Adhesiveness . . . Affinity for metal develops maximum adhesion providing permanent coating on gears.
Water Repellence . . . Effectiveness is not reduced by water.
Corrosion Prevention . . . Never acidic and will not etch or corrode.
Compounded Stability . . . Will not bleed or change physical condition within a greater temperature range.
Low Temperature Factors . . . Does not harden, crack or decrease in adhesion.
Abrasive Resistance . . . Repellent to adhesion of scale, metallics and other contamination.



A "mechanical brain" safety checks lubrication!

ALEMITE Accumeter®

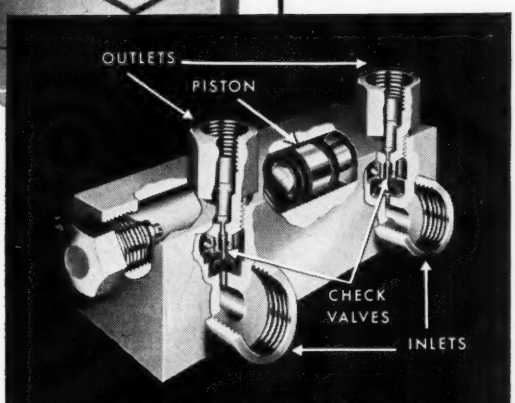
Assures automatic, foolproof lubrication under toughest conditions, on heaviest machines, indoors or out!

Imagine bearings operating under the very *worst* job conditions—in dust, rain, fumes, grit—even completely immersed. Now imagine what happens if you depend on ordinary manual methods of lubrication. Costly? Sure. Dependable? Hardly, may even be impossible.

That's the spot for Alemite Accumeter, the system with a control valve far more dependable than any man. The system that completely assures regular, proper lubrication, even under toughest conditions. Delivers the *exact* amount of lubricant where needed at the right time, *while the machine is in operation!*

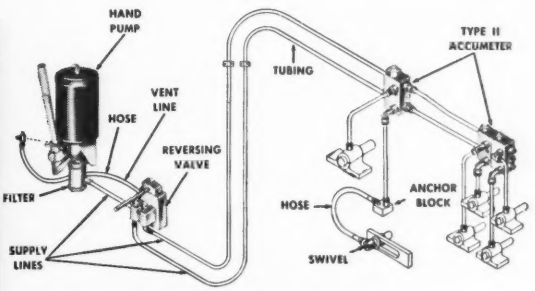
Costs, down-time, maintenance are all slashed by Accumeter—and output soars. That's why more than 95% of all major plants buying machine tools specify centralized lubrication!

And Alemite Accumeter Systems are easy to design into any machine. There is a system to solve any machine lubrication problem or combination of problems. See for yourself the tremendous operating advantages you offer when you specify automatic Alemite Accumeter.



Type II Accumeter Valves

Each serves two bearings. In four sizes delivering from .010 to .500 cubic inch of lubricant. Adjustable. Fully hydraulic—no springs. Completely sealed system serves up to 600 bearings. Manual or power operation.



Offers all these advantages!

- **Eliminates shut-down time for lubrication. Adds productive time to machine output.**
- **Seals completely against dirt, grit, fumes, water all the way from "barrel to bearing."**
- **Prevents bearing troubles due to neglect or wrong lubricant.**
- **Services all bearings—including those inaccessible or dangerous—in one operation.**
- **Avoids work spoilage and bearing repairs due to over-lubrication.**

Factory tested—field proved

Exhaustive, in-the-field tests show no appreciable variation in the amount of lubricant discharged after 73,312 lubrication cycles. Equal to 122 years of twice-a-day service!

ALEMITE

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A PRODUCT OF SW STEWART WARNER

FREE! ALEMITE ACCUMETER CATALOGUE

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Company .....

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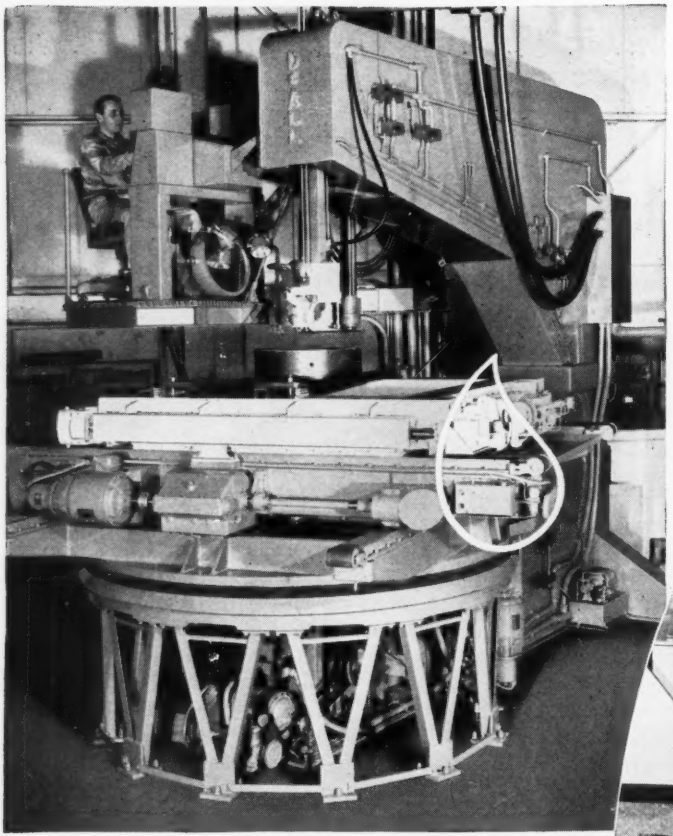
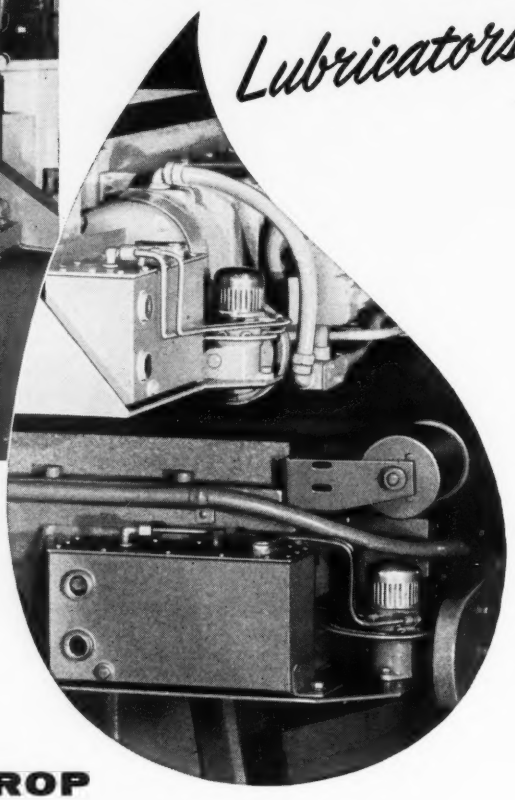


MACHINES OF GREAT PERFORMANCE USE THE MOST DEPENDABLE OILING SYSTEM EVER DEVELOPED

...MADISON-KIPP *Lubricators*



Two Madison-Kipp OL Lubricators installed on the world's largest band machine and die filer, manufactured by the DoALL Co., Des Plaines, Illinois...Operated by remote control, they machine 10-ton extrusion dies for the Air Force "Heavy Press Program."

Fresh Oil...

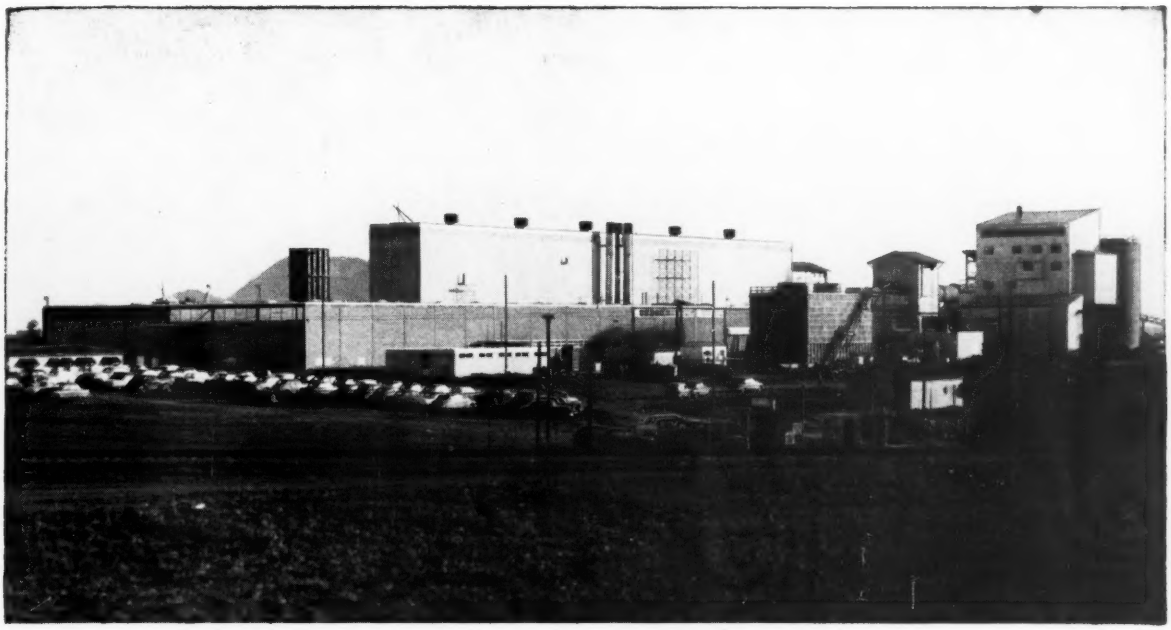
BY THE MEASURED DROP

...from a Madison-Kipp Lubricator is the most dependable method of lubrication ever developed. It is applied as original equipment on America's finest machine tools, work engines and compressors. You will definitely increase your production potential for years to come by specifying Madison-Kipp on all new machines you buy where oil under pressure fed drop by drop can be installed.

kipp

MADISON-KIPP CORPORATION
223 WAUBESA STREET • MADISON 10, WIS., U.S.A.

● Skilled in Die Casting Mechanics ● Experienced in Lubrication Engineering ● Originators of Really High Speed Air Tools



Lithium

Putting the "prod" in production . . .

Here's a bird's-eye view of the biggest step yet in meeting industry's continuing demand for Lithium. Lithium Corporation has put on stream a lithium plant with the largest potential capacity in the world. The $7,000,000.00 project located at Bessemer City, North Carolina is producing Lithium Carbonate and Lithium Hydroxide for industry at large.

Unique in the Lithium industry, Bessemer City is processing run-of-mine ore directly through its chemical plant, as well as concentrates. The former eliminates the once necessary step of first concentrating the ore. The plant treats company-owned deposits of spodumene ore reserves in the adjacent King's Mountain area. The concentrates are from Canadian sources. Coupled with the company's original plant at St. Louis Park, Minnesota, a substantial increase in present productive capacity of the lithium industry is assured.

Lithium Hydroxide and the Grease Industry

Now, for the first time, the grease industry can depend on a continuing source of lithium hydroxide, from inventory and available for immediate shipment. It also means that the industry need no longer hold back on lithium research projects. Company and industry-sponsored research can bank on the closest cooperation from Lithium Corporation's management team.

So, why don't *you* take a look at Lithium? It could hold the key to untold profits for *your* company. A card or letter will bring you complete information.

. . . trends ahead in industrial applications for Lithium.

LITHIUM CORPORATION OF AMERICA, INC.
2585 RAND TOWER
MINNEAPOLIS 2, MINN.

MINES: Keystone, Custer, Hill City, South Dakota • Bessemer City, North Carolina • Cat Lake, Manitoba • Amos Area, Quebec • BRANCH SALES OFFICES: New York • Chicago
CHEMICAL PLANTS: St. Louis Park, Minnesota • Bessemer City, North Carolina • RESEARCH LABORATORY: St. Louis Park, Minnesota

At its Burlington, New Jersey, plant...

Rheem Manufacturing Company

uses just one grease

for all applications involving high load, high speed, water hazard and wide temperature variations

"IT'S SHELL ALVANIA GREASE"

THE Burlington plant contains many giant presses, heavy production equipment and hundreds of secondary tools. All of this equipment is lubricated with a single multi-purpose grease . . . Shell Alvania.

Shell Alvania Grease is bringing outstanding machine protection and lubrication economy to plants from coast to coast. It is a true multi-purpose grease . . . shows remarkable indifference to heat, cold, water and machine speeds. In plant after plant, Shell Alvania Grease serves *every grease application* in the production setup!

ADVANTAGES OF SHELL ALVANIA GREASE:

1. **Shell Alvania Grease flows *freely* in cold temperatures, yet will not run out of bearings under excessive heat.**
2. **Ideal for wet, humid applications . . . it resists water emulsification.**
3. **Shell Alvania Grease has extremely high oxidation stability.**
4. **You'll find that Shell Alvania Grease extends time between greasings . . . a substantial saving in labor and grease.**
5. **Simple inventory . . . just the one grease to stock and apply.**

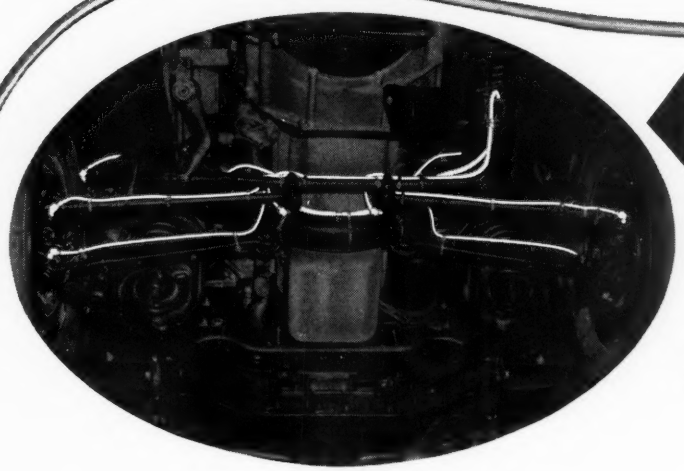
Why not let us show you how Shell Alvania Grease can save time and money in your plant. Write for technical information to Industrial Lubricants, Shell Oil Company, 50 West 50th Street, New York 20, N.Y.— or 100 Bush Street, San Francisco 6, California.

SHELL ALVANIA GREASE

The True Multi-Purpose Industrial Grease

SHELL®

NOW! nylaflow* lubricant lines outperform other tubing... yet often cost less!



IT'S NYLAFLOW* FOR THE LUBRICANT LINES in the new push-button power lubrication system for 1955 Lincoln and Mercury automobiles. Lincoln Engineering Co. of St. Louis chose NYLAFLOW tubing because it is dent proof and flexes as chassis members move. NYLAFLOW also costs less than other tubing tested, and is faster, cheaper and easier to assemble and install.

nylaflow* . . . the new flexible nylon tubing . . . is truly the modern flow line for lubrication systems. And here's why.

NYLAFLOW'S MADE FOR LUBRICANTS

It's chemically resistant to lubricants and any additives, inhibitors, etc., they may contain.

NYLAFLOW'S MADE FOR LUBRICATION SERVICE CONDITIONS

Because it stands up against constant rubbing and flexing, NYLAFLOW tubing solves problems of vibration and moving surfaces or connections. Another thing, NYLAFLOW is resilient to resist accidental blows.

SEND FOR NEW *NYLAFLOW* TUBING BULLETIN

NYLAFLOW'S MADE FOR EASY INSTALLATION

Flexible NYLAFLOW tubing eliminates pre-bending. What's more, it can be run in continuous lengths with the result that only two end connections are required—either standard metal compression or flare fittings.

NYLAFLOW'S MADE FOR COST SAVINGS

With all its superior performance, NYLAFLOW costs less than copper tubing (in some small sizes) or flexible hose of comparable bursting strength. NYLAFLOW tubing is supplied in stock diameters and lengths, and in two grades: Type T with a tested bursting strength of 1,000 psi and Type H, 2,500 psi. Sizes in production at this time range from ⅛" O.D. to ⅜" O.D.

THE POLYMER CORPORATION
of Penna. • Reading, Penna.

POLYMER *NYLAFLOW TUBING**
. . . nylon . . . Teflon . . . and other non-metallic shapes

In CANADA: Polypenco, Inc., 2052 St. Catherine W., Montreal, P.Q.

Teflon is the trademark for DuPont tetrafluoroethylene resin

*NYLAFLOW is the trademark for The Polymer Corporation's nylon tubing

Wherever throw-off, drip or squeeze-out is a problem...

USE SUNTAC OIL

OIL LEAKAGE MEANS:
higher lubrication costs
messy machines
hazardous oil slicks on the floor

SUNTAC OIL:
cuts leakage
lowers oil costs
minimizes hazardous floor conditions

In addition to its leak reducing properties, Suntac has all the high quality of expensive general-purpose oils. Suntac is fortified against oxidation to assure long oil life and against rust and corrosion to protect valuable machines. And, last but not least, because the leak-reducing agent is 100% petroleum, Suntac leaves no gummy film or residue.

For more information about Suntac, the oil especially made to prevent drip, throw-off and squeeze-out, see your Sun representative or write for your copy of Suntac Technical Bulletin to Sun Oil Company, Philadelphia 3, Pa. Dept. LE-8.

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INDUSTRIAL PRODUCTS DEPARTMENT

SUN OIL COMPANY

Philadelphia 3, Pa.

IN CANADA: SUN OIL COMPANY, LTD., TORONTO AND MONTREAL

2nd Annual
ASLE-ASME Lubrication Conference

October 10-11-12, 1955 **Hotel Antlers, Indianapolis, Ind.**

The American Society of Lubrication Engineers and the Lubrication Activity of the American Society of Mechanical Engineers will hold their second annual Lubrication Research Conference at Hotel Antlers, Indianapolis, Ind., on October 10-11-12. As in the 1954 Conference, there will be no conflicting sessions, and those attending will have the opportunity to hear the presentation of all papers. Registration fees (which cover preprints handed out): $3.00 for members, $7.00 for non-members.

TENTATIVE PROGRAM

Session I, Instability In Journal Bearings. (Monday AM) S. Abramovitz, Vice-Chrmn.

Definition Of Vibrational Terms For Journal Bearings, by Dr. Newkirk
Experimental & Theoretical Investigation Of Half-Frequency Whirl, by B. Sternlicht.
Experimental Investigation Of Resonant Whirl, by O. Pinkus

Session II, Recent Studies In Hydrodynamic Lubrication. (Mon. PM & Tues. AM) E. R. Booser, Vice-Chrmn.

Journal Bearing Operation At Super-Laminar Speeds, by M. I. Smith & D. D. Fuller
Journal Bearing Performance For Combination Of Steady, Fundamental & Low Amplitude Harmonic Components Of Load, by G. S. A. Schwaki
Studies In Lubrication, XI, by A. C. S. Ying, H. Charnes & E. Saibel
Analysis Of Elliptical Bearings, by O. Pinkus
Lubrication Of Infinite Composite Slider Bearings, by R. Davies & A. E. Roach
Predicting Performance Of Starved Bearings, by D. F. Wilcock
Measurement Of Lubricant Film In Journal Bearings, by W. E. Meyer, M. B. Purvis & F. J. Villforth
Finite Journal Bearings With Arbitrary Position Of Source, by J. D. Fedor
Temperature Effects In Hydrostatic Thrust Bearing Lubrication, by W. S. Hughes & J. F. Osterle
The Rheostatic Thrust Bearing, by Osterle & Saibel
Analysis Of Partial Journal Bearings Under Steady Loads, by J. C. Lee

Session III, Lubricants. (Tues. PM) S. R. Calish, Vice-Chrmn.

Physical-Chemical Study Of Engine Oil Performance, by Dr. A. Bondi
Determining Grease Consistency With An Automatic Worker-Viscometer, by H. J. Connor
Density-Temperature-Pressure Relations For Liquid Lubricants, by H. A. Hartung
Electrostatic Phenomena In Lubricating Systems, by H. J. Kaufman

Session IV, Rolling Element Bearings. (Wed. AM) E. E. Bisson, Vice-Chrmn.

Operating Characteristics Of High Speed Ball Bearings, by C. C. Moore & F. C. Jones
Effect Of Oyxgen In Atmosphere On Oil Lubrication Of High Temperature Ball Bearings, by Z. N. Nemeth & W. J. Anderson
Effect Of Synthetic Oils On Ball Bearing Fatigue Life, by H. V. Cordiano
An Apparatus For Fatigue Testing Roller Bearing Rollers, by C. P. Bacha

Session V, Boundary Lubrication. (Wed. PM) E. Rabinowicz, Vice-Chrmn.

Lubrication Of Friction Drives, by T. B. Lane
Thermal Aspects Of Galling Of Dry Metallic Surfaces In Sliding Contact, by F. F. Ling & E. Saibel
A Critical Temperature For Surface Damage In Sliding Metal Contact, by L. F. Coffin
Friction & Wear Of Several Metals Lubricated By Difluorodichloromethane & Similar Gases, by S. F. Murray, R. L. Johnson & M. A. Swikert

Complete, Clip, & Mail

Manager
Hotel Antlers
Indianapolis 6, Ind.

Re: ASLE-ASME Lubrication Conference
(October 10-12, 1955)

Please make the following reservation for:

Name_____

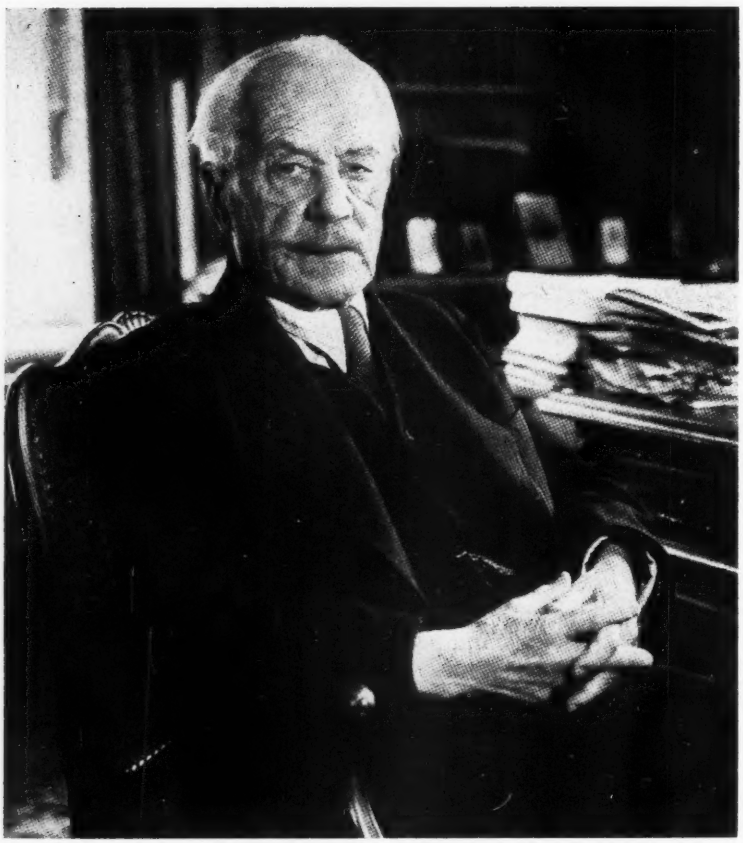
Address_____

Will arrive (day)_____, (date)_____, about (time)_____M.

Type Room Desired_____

RATES PER DAY

(A) For 1 person: $4.00, 4.50, 5.00, 5.50, 6.00, 6.50, 8.00 & 9.00; (B) One double bed for two persons: $6.00, 6.50, 7.00, 7.50, 8.00, 8.50, 10.00 & 11.00; (C) Twin beds for two persons: $8.50, 9.00 & 10.50; (D) Parlor Suites with twin beds: $13.00 & $17.50 Single or Double. If a room at the rate desired is not available, a room nearest that rate will be reserved.



ARNOLD SOMMERFELD

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Men of Lubrication

ARNOLD SOMMERFELD. The Science of Lubrication has been enriched by the attention of several great men of science and one of these is the illustrious mathematical physicist, Arnold Sommerfeld. Sommerfeld's contribution to the Theory of Lubrication is actually almost trivial when compared to his massive work in theoretical physics, but he is said to have derived great satisfaction from this work and from some other investigations in engineering science during a brief technical period in his career. The student of lubrication theory has good reason to be grateful for the brilliant contribution that Sommerfeld has made in the most important and the most difficult problem of the subject.

Arnold Johannes Wilhelm Sommerfeld was born in Konigsberg, East Prussia, in 1868. He died in 1951 as the result of a traffic accident.

Sommerfeld received the degree, Dr. Phil., in Konigsberg in 1891. From 1893 to 1897 he served as assistant in the Mineralogical Institute in Gottingen and as assistant to the famous mathematician, Felix Klein. From 1897 to 1900 he was professor of mathematics at the Mining Academy in Clausthal. From 1900 to 1906 he was professor of mechanics at the Technische Hochschule in Aachen. It was here that Sommerfeld did his technical work including his famous paper on lubrication theory. Following his period at Aachen, until his retirement in 1935, he was professor of theoretical physics at the University of Munich where he succeeded Ludwig Boltzman, famous for his work on kinetic theory of gases and on radiation.

Sommerfeld's interest in technical work was characteristically productive. His papers on interaction between electric generators working on the same power line and on the braking of trains are of lasting value in their fields. His paper "Zur hydrodynamischen Theorie der Shmiermittelreibung" (Z. Math. Phys. 50, 1904, p. 97) has been invaluable in the various mathematical problems which arise in the theory of lubrication of journal bearings. Osborne Reynolds, in his famous paper "On The Theory Of Lubrication," applied his (Reynolds') theory to the results that had been reported by Beauchamp Tower on his work on journal bearings. But Reynolds was forced to the use of infinite trignometric series in order to perform the integration for the bearing load. If one cares to consult Reynolds' paper, it will be seen that this leads to long and involved mathematical work. The method is also unsatisfactory because the series did not converge for values of eccentricity greater than 0.5. Fortunately this did not affect its application to Tower's results, but it was a great handicap to a general application of the theory to journal bearings. Sommerfeld proposed an ingenious substitution which makes it possible to perform the load integration in closed form for all values of the eccentricity. This has been of the greatest value in helping to understand the still far from complete theory of journal bearing lubrication.

But Sommerfeld's connection with lubrication and engineering science seems almost accidental. His great work was done in the field of what is sometimes called "the new physics", that is, the physics of the quantum theory and the theory of relativity, and his influence in spreading these ideas was great. As recently as fifteen years ago the work of men like Sommerfeld was unknown in any popular sense and had almost no interest for engineers. But from it has come the present day science of nuclear physics, with its awesome possibilities for good or bad, and engineers have been given a new science to apply to man's service.

Sommerfeld's training was in the classical problems of mathematical physics, and it is an interesting side light on the trends in science to observe how these old methods were applied by him to the new problems of quantum physics and wave mechanics.

The physicist, W. Heisenberg, on the occasion of Sommerfeld's eightieth birthday said "not only did Sommerfeld have students — he developed practically a whole generation of theoretical physicists who are now widely distributed over the world." He appears to have had an extraordinary ability as a lecturer and men from all over the world came to his Institute for Theoretical Physics to study under him, among them several who have since won Nobel Prizes. It has been said that his activity as a teacher has left more far reaching effects than his great success as an investigator.

Sommerfeld visited the United States on three occasions: in 1922 he served as Karl Schurz professor at the University of Wisconsin, as visiting professor at the California Institute of Technology in 1928, and in 1931 as visiting professor at the University of Michigan. He was a member of many learned societies and he received much recognition for his work in science. His course of lectures on theoretical physics have been published in book form and occupies six volumes. The series entitled "Lectures on Theoretical Physics" cover mechanics, the mechanics of deformable media, electrodynamics, optics, thermodynamics and statistics, and partial differential equations. All these volumes except the one on thermodynamics and statistics have appeared in English translation. He was engaged on this volume at the time of his death.

Sommerfeld is said to have had a delightful home life. He was very fond of classical music and of mountain climbing and skiing. In his younger days he often went on skiing trips with his students. His liberal politics appears to have caused him some unpleasantness during the Nazi period. His great

(Continued on Page 283)

(This is the fourth in a series of articles by F. R. Archibald, Analyst, of Arthur D. Little, Inc.)

Neutrons, Gamma Rays, & Wear

by A. Hundere, G. C. Lawrason & J. P. O'Meara*

There have been mixed feelings in regard to the use of radioactive tracers for studying wear. Some seem to have the same fear for radioactive tracers that the layman has for the atom bomb and, as a result, will not consider their use. Others will not allow tracers in their laboratories unless extreme precautions are taken, such as isolating all apparatus equipped with radioactive parts in a separate and special room. Others do not consider wear measurements made by the use of the radioactive tracer technique to be significant. We have found that radioactive tracers can be safely handled in a relatively simple manner and that they not only greatly accelerate the accurate determination of wear, but they also permit making certain wear studies that cannot be made by any other presently known method. The purpose of this paper is to summarize briefly our experiences and results obtained in utilizing the radioactive tracer technique for studying wear. It is hoped that in so doing we may contribute to more effective utilization of a technique, which we believe to be of great importance in increasing our knowledge of wear.

A brief historical note might be in order before proceeding further. The radioactive tracer technique for evaluating wear was patented in 1941 by Ferris of The Atlantic Refining Co.[1, 2] Incidentally, we are licensed under this patent. Ferris was unsuccessful in making the technique practical because at that time the only source of artificially radioactive tracers was the cyclotron. As a result, he had to introduce his tracer, phosphorus, at the very beginning of the manufacturing process, i.e., adding it in the foundry as a component of the ring material. Because of the short radioactive life of the phosphorus isotope and because of the rather lengthy time required to cast, machine, and install the rings, a very insensitive test was obtained. In 1947 Primo Pinotti of California Research Corp., without knowledge of the Atlantic patent, conceived the idea of utilizing a nuclear reactor to obtain radioactive parts via neutron bombardment.[3] This greatly simplified the procedure and also resulted in much higher activity, thereby making the technique a practical tool for wear studies.

SAFETY PRECAUTIONS. The first questions one asks when considering utilizing hazardous materials pertain to safe handling. Like fire, radioactive materials deserve a great deal of respect, even more so because you cannot see the rays that pierce you and cause harmful effects if they exceed safe limits. Also like fire, radioactive tracers can be easily and safely handled when rather simple rules are followed.

The people handling radioactive materials are closely supervised. The Atomic Energy Commission sees to this. All the sources of radioactive tracers are under AEC control, and one does not receive authorization to obtain them until he has convinced the AEC that he is competent to follow the rules for safe handling. This means filling out AEC Form 313A. The AEC will also educate you to a certain extent, telling you how to protect yourself by using survey meters, dosemeters, film badges, etc. A survey meter is the same black box that one uses for looking for uranium, i.e., a Geiger counter. Its name is descriptive of its use. You use it to survey your laboratory and equipment to determine safe exposure times or shielding requirements in the vicinity of radioactive materials or parts. The dosemeter is a fountain pen size instrument that is supposed to tell you the total radiation to which you have been exposed. This qualified statement results from the fact that we have been unable to

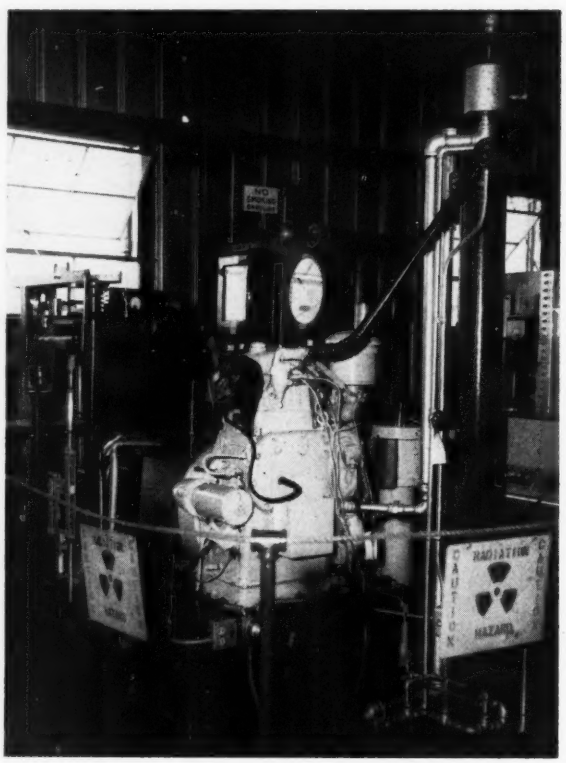

Fig. 1. G.M. 1-71 Engine, equipped for radioactive wear studies.

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find a satisfactory dosemeter. As a result, each man exposed to radiation also wears a film badge as a further check on the amount of radiation to which he has been exposed.

The major problem that one encounters in introducing radioactive tracers into the laboratory is that of educating the shop personnel who are exposed to the radiation. You can tell them that the AEC says that radiation is safe if one is not exposed to more than 300 milliroentgens per week. The mechanic, however, will want to know what this means; and no matter how much technical lingo you may use, it is doubtful that he will understand what it is all about. You have to get your story across by talking in terms that he understands, and this seems to be best done by making a comparison with everyday radiation exposure. We are exposed to a normal background radiation from cosmic rays and naturally occurring radioactive material in the earth, in the air, and in our bodies that averages about two milliroentgens per week. If one carries a large radium dial watch in his pocket, this can amount to as much as 100 milliroentgens per week. About 2,000 milliroentgens of exposure are obtained during a dental X-ray unless your dentist is extremely careful. A rather complete X-ray examination of your body can result in localized exposure of as much as 20,000 milliroentgens. Such bases of comparison are very effective in convincing the shop personnel that they have nothing to fear from 300 milliroentgens of exposure per week.

Fig. 2. Installation of radioactive gear in Ryder gear machine.

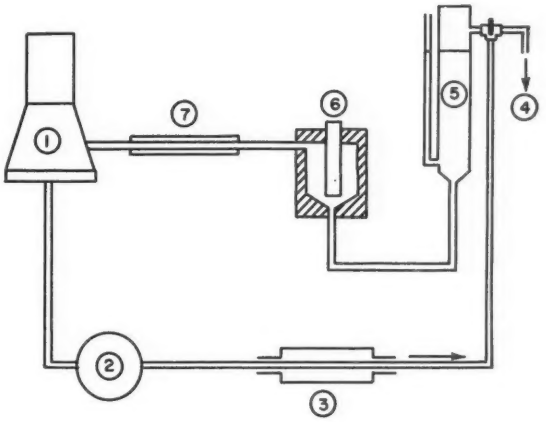

Fig. 3. Schematic diagram of oil system for radioactive ring wear studies. Key: (1) Test engine — dry sump; (2) Scavenge pump; (3) Cooler; (4) Dump; (5) Sump; (6) Lead-shielded Geiger tube; (7) Heater.

After working with radioactive tracers for two years, our shop personnel take them in stride, and we can specify the use of radioactive tracers for measuring wear in much the same manner as we would specify the use of any other tool. We are now safely handling radioactive gears weighing over one pound — 560 grams to be exact — that have been activated for ten days at a flux density of 3×10^{12} thermal neutrons per square centimeter per second. When they are removed from the pile, these gears have an activity that is equivalent to about 160 millicuries. (A millicurie is the activity given off by one milligram of radium.) In our laboratory we make no attempt to centralize our equipment for radioactive wear studies. Any piece of equipment in the laboratory may be selected, and we simply mark the area with the designated AEC signs. Fig. 1 shows one of our typical installations.

Since the radiation level varies as the square of the distance from the source of radiation, one of the greatest safety measures is to increase the distance. For this reason long-handled tools are utilized in handling radioactive parts. Fig. 2 shows an operator installing a radioactive gear. Similar long-handled tools are used for installing piston rings. All of these special tools we use are inexpensive, and they are simple enough to use that the increased installation time is quite small. It should be pointed out that the longest tools are not always the safest because of the time factor that is involved. The further the workman is away from his work, the more difficult it is for him to accomplish his task and, therefore, the greater the time required. The safest tools are those that result in the minimum value for the installation time divided by the square of the distance.

In almost any wear study it is necessary to make inspections of the wearing surfaces in order to evaluate them for cleanliness, corrosion, scuffing, etc. Therefore, it is necessary to devise safe ways for making such inspections of radioactive

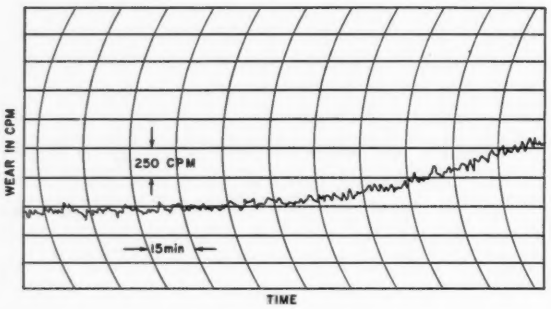

Fig. 4. Wear-Time Chart.

parts. If we want only to make macroinspections, this is usually done by inspecting the parts behind a lead shield, utilizing a mirror for the observations. For microinspections, we have built a three-foot periscopic microscope that is 18 power. We also make photomicrographs utilizing the equipment shown on the right in Fig. 2. We have found that the radiation has no measurable effect on the film for the short periods required for taking the photographs.

ACTIVATION OF PARTS. After one knows that he can safely handle radioactive parts, the next thing he wants to know is where, how, and what can be activated, and how much it costs. There are a number of ways of making engine parts radioactive, but at present the most convenient and practical way is that of subjecting them to neutron bombardment in a nuclear reactor (atomic pile). Many people think that Oak Ridge is the only place to have parts so activated when, actually, the Oak Ridge reactor used for this purpose is one of the least desirable from the standpoint of flux density. This reactor was one of AEC's first reactors and, since it was built, there have been many constructed with much greater flux densities. Reactors offering suitable irradiation facilities are located at the Brookhaven National Laboratory on Long Island, New York; the Argonne National Laboratory near Chicago; the Oak Ridge National Laboratory at Oak Ridge, Tennessee; the Materials Testing Reactor at Idaho Falls, Idaho; and the Chalk River Reactor in Canada. These reactors differ widely in flux density, hole sizes, temperature, shutdown schedule, and service charges. The facilities being made available are continually changing, so no attempt will be made to list them here. We have found the Brookhaven four-inch square hole facilities at a thermal neutron flux density of 3×10^{12} to be satisfactory for most of our rings and gears, and larger rings have been irradiated in the 12-inch square hole at 1×10^{12}.

It is necessary to be concerned about corrosion and temperature effects while the material is in the reactor. In some cases it is necessary to encase the parts in a sealed aluminum container. At Brookhaven, where we have had most of our parts activated, the humidity in the reactor is so low that rusting is not encountered. Although the temperature is about 200 C. in the reactor, we have observed no apparent physical effects on the rings and gears that we have had irradiated to date. However, if the activated part is so large that heat transfer from the center is poor, gamma heating may have to be taken into account. In addition to corrosion and temperature effects, one must consider the effect of radiation on the physical properties of the material. The published data have shown[4] that massive radiation dosages have a large effect on the physical properties of some materials. The only measurements that we have made have been for hardness, and no measurable change has been detected. In comparing the absolute wear of radioactive parts with non-radioactive parts, we have been unable to detect any differences. One should not expect that the amount of radiation during activation would be sufficient to have any significant physical effect because the activities used for wear studies are very low. Only one atom per 200 million is made radioactive in the ten days of irradiation of iron at a neutron flux of 3×10^{12}.

The people in charge of the AEC reactors are very fussy about what they put into them, and rightly so. It is necessary to tell them the complete composition of the material being irradiated. This information is needed to determine what handling procedures and what safety precautions must be taken in removing the material from the reactor. Some materials become much more radioactive than others. Manganese, for example, is such a material. One-half percent of manganese, as an alloy or an impurity, will cause about a thousand times the activity of the remaining material, assuming it to be iron. Therefore, Brookhaven must take this into consideration when the material is removed from the reactor. This high activity of manganese, however, will be of no concern to the user because its half-life is only 2.59 hours. As a result, during the time required for shipment and installation, the manganese will have decayed to a very low level. After the irradiated parts are removed from the reactor, they must be placed in special shipping boxes made to Bureau of Explosives specifications in order to meet ICC regulations. Although these boxes can be rented from the AEC reactor operating organi-

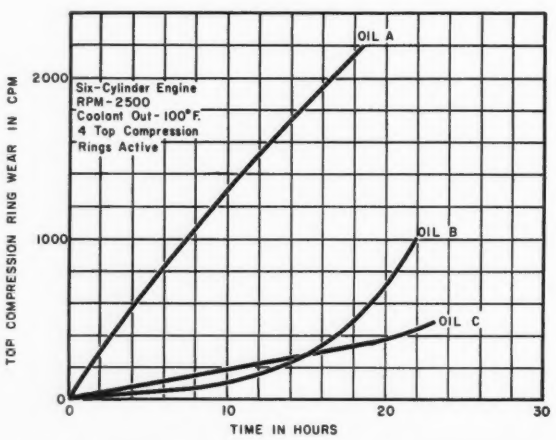

Fig. 5. Wear under low jacket temperature conditions.

zation, they usually prefer that you furnish your own. These boxes are heavily lead-shielded, and the boxes we use for six piston rings weigh approximately 300 pounds. The ICC requires that sufficient lead shielding be used so that the radiation on the surface does not exceed 200 mr per hour. Our shipments seldom approach half this value. The boxes can double as storage containers until the radioactive parts are used.

It might be well to discuss at this point the matter of activity decay. This is normally referred to as half-life, which is the time required for the activity to decay by one-half. Table I gives the half-lives of the most common constituents of steel. It must be remembered in working with materials such as iron and steel that the half-life varies with time due to the half-life differences of the constituents. The half-life of a steel might be two hours when it comes out of the reactor, but by the time it is received, the half-life may have increased to 40 days, and after several months it may increase to as much as 60 or more days because the short-lived constituents have become less influential on the total activity.

TEST PROCEDURES & INSTRUMENTATIONS. After one has a source of radioactive parts and knows how to handle them safely, the next question is what procedure should be used and what instrumentation is best. The answer is not only very complex, but more often than not, the answer is a matter of opinion. Within the limitations of this paper, we can only briefly tell you about our experiences.

In the first paper presented on the use of radioactive tracers for determining engine wear,[3] the California Research Corporation described a sampling procedure. The radioactive part was the top compression ring. They determined the wear by withdrawing samples of oil from the crankcase and counting the activity with a Berkeley scaler. At the start of our work, we adopted a continuous sampling procedure as illustrated in Fig. 3, which is a diagrammatic sketch of the system used for all our radioactive wear studies. The oil is circulated over a gamma-sensitive Geiger tube within an immersion shield. The Geiger pulses are counted by

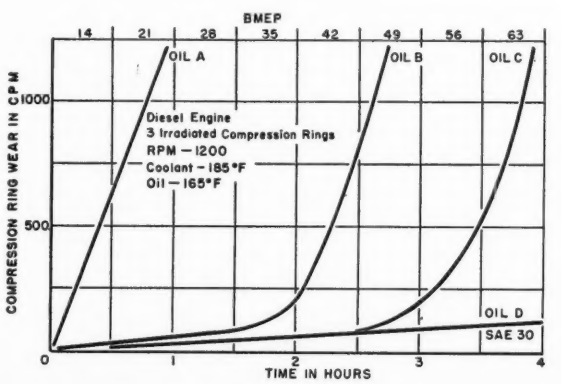

Fig. 6. Wear characteristics of light (Arctic) oils.

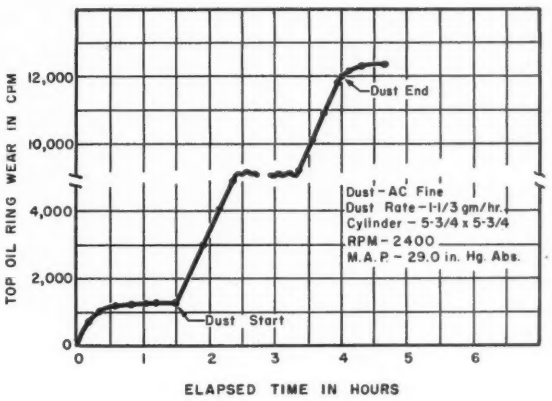

Fig. 7. Wear from air inducted dust.

a Tracerlab Ratemeter, and the reading is recorded continuously on a chart recorder to obtain a wear chart such as is shown in Fig. 4. We believe this system is easier to use and that the added information obtained is normally very advantageous in most wear studies. There are times, however, when it is preferable to use the sampling procedure, such as when the continuous system cannot be conveniently installed or the complication of the continuous system is not warranted.

If the most important wear measurement is total wear rather than the shape of the wear curve, then a scaler usually gives greater accuracy of counting. In about half of our programs we have used a Berkeley scaler with good success. We have found that the best way to increase the accuracy and/or sensitivity of radioactive wear measurements is to increase the cpm per milligram of metal removed. This can be done by leaving the parts in the reactor longer, using a hotter reactor, by using a number of radioactive parts instead of one (such as six piston rings rather than one), or by decreasing the volume of oil in the system. Another way of obtaining greater accuracy is by using a scintillation counter. This instrument, which has only recently become available, detects the light emitted from a special phosphor when radiation passes through it. Is is generally much more sensitive to gamma rays than are conventional Geiger counters, so the effective counts per minute per milligram of metal removed is much higher. Although we are experimenting with scintillation counters, we have not made use of this instrument to date because we have been able so far to obtain the accuracy of wear measurements we need using a Geiger tube.

Geiger tubes are not all the same. Some are temperature-sensitive, which is very undesirable. Since high temperature shortens the life, we attempt to design our oil systems in order to avoid exceeding 200 F. Our average tube life has been about 200 hours of operation.

Reducing background activity is very important in obtaining accuracy of radioactive measurements. With continuous systems where the Geiger tube is located relatively close to the radioactive parts, a large part of the background activity is due to the

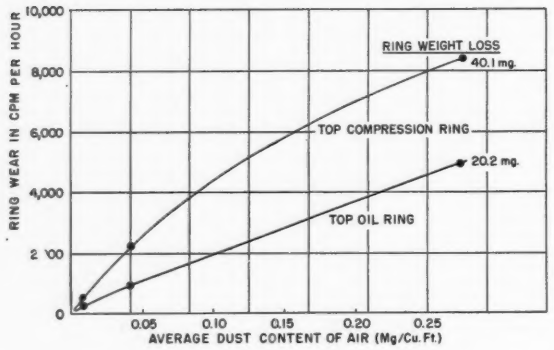

Fig. 8. Effect of inducted dust on ring wear.

proximity of the radioactive parts themselves. Even when the activity is determined at a remote location, such as in the sampling procedure, there is still background radiation to be concerned about. Actually what is important is the ratio of the cpm rise due to wear to the cpm background level. Since lead is relatively cheap compared to other costs, we use very heavy lead shielding and endeavor to get our background count down to 150 counts per minute or less.

Another very important factor is the tendency of the larger metal wear particles to drop out of suspension. This is a function of the velocity of the oil, particle size, and configuration of the oil system. It is desirable to keep the velocity of the oil as high as conveniently possible and eliminate all stagnation areas. Eliminating stagnation areas includes making the surfaces in contact with the oil as smooth as possible. Smooth surfaces also greatly facilitate the cleaning of the radioactive particles from the system. A check on the rate of particle drop-out can be made by stopping the oil flow at the end of a wear test and noting the change in the activity reading. The checks we have made indicate that the drop-out of radioactive particles has had no effect on our results providing that we complete each test without stopping circulation of the test oil.

The question always arises as to how far one can trust the reading of this black box called the ratemeter or scaler, and also how one can tell when it isn't giving the correct reading. As a result, an instrument check is necessary. We first used a lead-shielded container that was filled with uranium salt (uranyl acetate) to give an activity reading equal to our average wear ratings, but the temperature difference between the oil sensing well and the standardization cell was undesirable. To correct this and to simplify the procedure, the source of constant radiation was changed to a standard radioactive cobalt probe that is inserted in a hole drilled into the shielding of the sensing well. This hole is located over the center of the tube and is of such depth to give a cpm rise equivalent to the average wear measurements. It has been thought that this may result in an error in calibration due to the fact that the radiation of the cobalt is not the same as that from the radioactive material used in the wear studies. There have been no indications of this, however, from the limited checks we have made.

We have found that there are other things besides radiation that will trip the Geiger counter and give erroneous cpm readings. For example, we have experienced trouble from signals generated from the high voltage ignition used on spark ignition engines, and at times have found it necessary to use a Faraday screen between the ignition system and the counting equipment. The continuous counting system with a chart recorder is advantageous for detecting this and other such spurious counts. Also, since such signals are entirely different from those from gamma radiation, they can be easily detected with an oscilloscope. Although the radioactive technique is best suited for relative wear measurements, it is often needed for obtaining absolute wear data. We have found, however, that the obtaining of absolute wear measurements using the radioactive technique is often quite difficult. In our procedure we dissolve in acid a minute piece of the radioactive material used in the wear study and then add a base for neutralization in order to obtain a neutral solution that can be put in the sensing well. The resultant cpm per milligram value can then be utilized for converting the cpm measurements into milligrams of metal removed. When radioactive chrome rings were utilized, we experienced difficulties in preparing such a solution, due to the insolubility of the chrome salt in neutral solution. We finally resorted to using a highly acid standard solution which was compared with an oil sample in a glass sensing well. We have also experienced difficulty using this procedure with iron piston rings because of the difficulty of determining the amount of radioactive material that goes out the exhaust. Data have been presented[3] showing that radioactive wear measurements will check ring weight loss determi-

Table I. Half-Lives and types of radiation.

Isotope	Half-Life	Type of Radiation
Fe^{55}	2.9 years	Beta, no gamma
Fe^{59}	47 days	Beta and gamma
Si^{31}	2.6 hours	Beta, no gamma
P^{32}	14.3 days	Beta, no gamma
S^{35}	87 days	Beta, no gamma
Cr^{51}	27 days	Gamma, no beta
V^{52}	2.6 min.	Beta and gamma
Mn^{56}	2.6 hours	Beta and gamma
Co^{60}	5.2 years	Beta and gamma
Ni^{65}	2.56 hours	Beta and gamma
Mo^{99}	67 hours	Beta and gamma
Mo^{101}	15 min.	Beta and gamma
W^{181}	140 days	Gamma
W^{185}	73 days	Beta and gamma
W^{187}	24 hours	Beta and gamma

nations if it is assumed that the activity of the oil consumed is the same as that in the sump. We have found that this does not always hold true. We, therefore, endeavor to check our radioactive ring wear against ring weight losses.

At this point it might be well to mention the matter of disposal of the radioactive waste that always results in any radioactive study. The AEC has disposal facilities that are available at a nominal fee. There are also commercial concerns set up for the disposal of radioactive waste products. One can dispose of his own material if the AEC specifications for the disposal of radioactive waste are followed. This requires that the parts be encased in concrete and dropped at sea where the depth of the water is not less than 1,000 fathoms. The handling of radioactive material for disposal can be greatly simplified if it can be stored for a rather lengthy period so that decay will drop the level of activity. We have been following this practice. It so happens that we have an abandoned deep well in one corner of our laboratory. Used piston rings, gears, etc., are lowered into this well in containers. We will, therefore, be able to store our radioactive waste conveniently for a sufficient period for its activity to drop to a low level. This well permit us to operate for several years before requiring final disposal.

In radioactive wear studies one always ends up with large quantities of radioactive oil. We have followed the practice of burning this oil in a pot burner and disposing of the ash in the same manner as the used radioactive parts. We have found that when the radioactive oil is properly burned, there is no activity in any of the gaseous products of combustion.

WEAR RESULTS. So much for the test technique itself. Next let's discuss some of the more interesting results that we have obtained.

Corrosive Wear. In using the technique for piston ring wear studies under low jacket temperature conditions, we have found that it is possible to obtain a much clearer picture of the effect of lubricants on corrosive wear. When continuous wear curves are established for different oils, results such as shown in Fig. 5 are obtained.

These data are from a six-cylinder automotive engine with a radioactive standard compression ring in Cylinders 1, 3, 4, and 6. The continuous system of recording the radioactive iron in the oil was used. All three oils designated in Fig. 5 contain additives to qualify them as heavy duty oils. Oil A has practically no tendency to neutralize the acids causing wear. Oils B and C contain definite neutralizing additives, but differ considerably in their behavior. When such oils are run for a sufficient period, the additives lose their ability to prevent corrosive wear and their performance becomes essentially the same as that for non-additive oils. It is believed that obtaining the complete wear curves as shown in Fig. 5 greatly increases our knowledge of the effect of lubricants on corrosive wear. The radioactive technique is by far the simplest and easiest means for obtaining such curves.

In running some oil-fuel combinations, we have encountered considerable difficulty as a result of nonrepeatability of the test. When the oil-fuel combination is one that gives a clean piston, the repeatability has been very satisfactory. However, when the oil-fuel combination gives a dirty engine, we have experienced poor repeatability. We believe that this is the result of lacquer formation on the cylinder wall and rings that causes erraticness in the rate of wear. We have had some success in correcting this by bracketing each test by a run on a high detergent oil to purge out the lacquer deposits.

Load-Carrying Ability. One of the most successful applications we have found for the radioactive technique has been in the development of a test method for determining the load-carrying ability of Arctic oils. These oils are light 5-W type oils that have exhibited poor or borderline load-carrying ability in many engines, and especially from the standpoint of piston ring wear. This work has been sponsored by the Bureau of Ships to assist in the development of improved 9005 oils for sub-zero use. The engine used in this program has already been shown in Fig. 1. It is a one-cylinder, two-cycle Diesel engine of 71 cubic inch displacement. A continuous system of recording the radioactive iron in the crankcase was again used. In the first tests a cold chrome ring was used in the top groove and the three other compression rings were standard radioactive iron rings. In later tests three and four radioactive standard chrome rings were used. To our knowledge this was the first application of radioactive chrome rings. In 1945 some work was done at Massachusetts Institute of Technology using radioactive chrome which was plated on chrome rings.[5] Although chrome has a half-life of only 26 days compared to 47 days for iron and it wears at a considerably slower rate than iron rings, the sensitivity obtained is comparable. The reason for this is that chrome has a specific activity of approximately 26 times that of iron, i.e., one milligram of chrome gives off 26 times as much radiation as iron for our normal irradiation period. Radioactive chrome rings will be discussed further later in the paper.

Getting back to the test for load-carrying ability, the test procedure consists of establishing a wear versus time curve for each oil by operating the engine under a schedule of increasing bmep until the total wear reaches a certain amount or the limit of the engine is reached. By experimentation it was found that if the test is stopped before the wear rate exceeded a fixed amount the rings do not scuff to the point of affecting the repeatability when a series of tests are made on a given set of rings. Typical results from this program are presented in Fig. 6. These data were obtained using three radioactive iron compression rings in the second, third, and fourth grooves. When radioactive chrome rings were used, the results were essentially the same. In Fig. 6 Oil A was so poor in load-carrying ability that it caused a high wear rate at the lowest loads. Oils B, C, and D are shown to have essentially the same wear characteristics up to some load (different

for each oil) where the curve breaks. It is believed that this knee in the curve represents the load at which the lubricant changes from hydro-dynamic, or quasi-hydrodynamic, to boundary lubrication. It has been found that when the rate of wear is as high as that shown for lubricants A, B, and C, the piston rings will scuff if the test is continued. This procedure has been utilized for determining the effect of many operating and lubricant variables on load-carrying ability. When the procedure is used to rate lubricants, each test oil is bracketed by a test on a reference oil, and the results are expressed as a relative rating.

Effect of Dust on Wear. We have found that the radioactive technique is a very effective tool for studying the effect of dust content of the intake air on piston ring wear. This work was sponsored by Detroit Arsenal. The tests were conducted in an air-cooled 5¾ x 5¾ cylinder. The procedure utilized was the same as that discussed above for the other piston ring wear tests. Chrome piston rings were utilized. Because of the high wear rates that were to be encountered, special piston rings were obtained which were identical to the standard rings except that the chrome thickness was increased to .015 on the compression ring and .008 on the oil control rings. With this amount of chrome, extensive wear data could be obtained before the chrome would wear through. Since it was necessary to determine the rate of wear for each individual ring, one piston ring was installed at a time. Typical results obtained from this test are illustrated in Fig. 7. The dust used was the standardized dust made for the testing of air cleaners. The final results obtained showing the effect of dust content on piston ring wear are presented in Fig. 8. These data illustrate the great influence of dust on piston ring wear. In a severe dust storm the dust content is as high as 40 milligrams per cubic foot. Because dust has such a great effect on engine wear, it is extremely important in any wear study, and especially in a study of piston ring wear, that the dust content of the inducted air be very carefully controlled.

Since in these dust tests it was necessary to obtain absolute wear measurements of the ring faces only, the question arose as to how much of the total activity resulted from piston ring side wear. It was possible to determine the amount of the total activity due to side wear because this was iron activity and could be differentiated from the chrome activity by using a gamma ray spectrometer. This instrument differentiates between the radiation from different materials because the energies of their radiation are not the same. Such an instrument opens interesting possibilities in wear studies because one can simultaneously determine the wear of several parts of an engine if there are sufficient differences in the metals. This can be accomplished by plating on metals with the required activity dissimilarities, providing, of course, the change in metal will not have a diverse effect on the wear phenomena being studied.

Another method we have considered for studying the wear rates of two surfaces simultaneously is by having one of the two surfaces of such composition that one gives off beta radiation and the other gamma. The combined beta and gamma counts per minute could then be read with a thin window tube and the gamma radiation determined by inserting a shield to cut out the beta radiation.

If one is studying wear under conditions of boundary lubrication, any change in composition of the wearing surfaces cannot be tolerated. On the other hand, if one is interested in only determining the transition from hydrodynamic lubrication to boundary lubrication, the composition of the surfaces is relatively unimportant.

Gear Wear. Another interesting application that we have found for the use of the radioactive tracer technique has been in the study of gear wear. We will touch only briefly on this work, due to the fact that there is another paper being presented on this subject. A photograph of our test set-up has already been presented in Fig. 2. This is a Ryder, four-square, power-circulating, gear machine utilizing spur test gears. The test oil system is of the continuous monitoring type as described above, and the wear is recorded continuously on a strip-chart recorder. The sensing well is located only 37 inches from the radioactive gears, and this proximity of the Geiger tube to the radioactive mass of the 560-gram test gear necessitates very heavy shielding in order to get the background down to the required level.

The standard procedure for determining the load-carrying ability of gears is to load the gears until a fixed amount of wear or scuffing occurs and to define the load at this point as the lubricant rating. Since it is not possible, or at least impractical, to obtain perfect gears, one always has the gear variations affecting the lubricant ratings. It would, therefore, be highly desirable if one could compare the load-carrying ability of an unknown oil with a reference oil on the same rubbing surfaces. Several ways of accomplishing this with gears have been tried. It is not as simple a matter with involute gears as it is with piston rings due to the change in gear tooth profile that accompanies wear. As a result, the load-carrying ability increases greatly with wear. Although this program is not complete, indications are that we will be able to largely eliminate the gear variations in rating lubricants by first establishing a base wear curve on a known straight mineral oil. We hope to have further to report on this in the not too distant future.

CONCLUSION. The only concluding comment that we wish to make is that we believe that the radioactive tracer technique can be easily and safely utilized for wear studies and that it is a powerful tool for increasing our knowledge of wear.

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COMMENTARY, by C. R. Lewis (Chrysler Corporation). This paper is an excellent summary of the advantages which can be obtained by the use of radioactive tracers in wear measurements and of the pit-falls which must be avoided to obtain useful results.

As a matter of historical interest, radioactive tracers were used in wear studies as early as 1941 by J. T. Burwell at the Massachusetts Institute of Technology in a research project sponsored by the Chrysler Corp., quite independently of The Atlantic Refining Co. work. Professor Burwell used cyclotron activated manganese as his tracer isotope in steel, and measured primarily the amount of metal transferred from one wearing surface to a mating one. This transfer method of utilizing radioactive tracers to study wear has not been mentioned in the present paper. Although it is not well adapted to the measurement of total wear over long periods of time, it can be used to demonstrate wear patterns and, in particular, to determine the distribution of wear over a given sample surface.

When this method of determining metal transfer is applied to the piston ring and cylinder bore of an engine, it shows after a few minutes running the familiar pattern in which the largest wear rate is found at the top of the ring travel, and a secondary maximum at the bottom of the stroke with smaller wear rates in the central part of the cylinder where the piston speed is highest. In some cases an area in which no transfer has taken place is found corresponding to the piston ring gap, showing that in this particular test ring rotation did not occur.

Perhaps one of the most striking results which can be obtained from a test of this type is a demonstration of the relatively large amount of material which can be transferred between piston ring and cylinder wall. In some of our tests only the top piston ring is made radioactive, but an autoradiograph of the cylinder wall taken after a half hour engine operation shows clearly the position at top dead-center of not only the active ring but of all of the other piston rings. Such an autoradiograph shows how material is transferred a number of times back and forth between the piston rings and cylinder wall without being removed as wear particles.

Transfer of this metal is not necessarily confined to soft materials or to mating materials of similar hardness. In studying the side wear of piston rings by this method, we have found chromium transferred from a piston ring to the very much softer lands of an aluminum piston.

Where total wear is to be observed, as in the evaluation of lubricants, the method described by the authors can give results much more rapidly and conveniently than conventional wear measurements. However, where the location and extent of wear areas are of interest, as in studying metallurgical factors and the effects of surface contour changes, the measurement of material transfer can have definite advantages.

AUTHORS' CLOSURE. We first wish to thank Mr. Lewis for his kind words and for his report on studying metal transfer utilizing radioactive parts. Although we have made some use of this technique, we neglected to say anything about it in our paper. Our limited experience confirms the thoughts expressed by Mr. Lewis. At times we have found that in addition to wanting to know the total wear, it is of interest to know the extent of metal transfer. The obtaining of radiograms from non-radioactive parts in contact with radioactive parts is a most effective way of accomplishing this. In fact, it is the only way we know of for determining very small amounts of metal transfer.

New Products

Multi-Cartridge Oil Filters. New multi-cartridge oil filters combining versatility with operating convenience have been introduced that are recommended for a wide range of applications: engine lube and fuel oils, hydraulic oils, industrial cutting oils and coolants, air filter oils—virtually any operation where oil can be bypassed. The flexibility of these units lies in the fact that six different types of cartridge refills may be used interchangeably. Each cartridge is designed to do a specialized filtering job depending on type of oil, flow rate required, kind and degree of contamination, and other variable factors. Available in ten sizes using one to 24 cartridges to meet all capacity requirements, and suitable for individual machines, central systems, or batch filtration, all models feature quick opening covers for convenience in changing cartridges. Covers are fastened by swing bolts which can be loosened quickly; large models have unique lifting device that raises and swings cover to one side. A permanent neoprene gasket seals the cover tightly to the filter tank. Cartridges are sealed by means of a removable pressure plate; spring on plate compresses when cover is closed, locking cartridges firmly in position. (Bulletin 201, Houdaille-Hershey of Indiana, Inc., LE-11/4, 818 Wabash Ave., Lebanon, Ind.)

"The Gits Airliner," "an entirely new approach to air line lubrication," atomizes the oil in a chamber remote from the air line—only oil mist is injected into the air stream. Lubricating any volume of air from ¾ cu. ft. up to capacity of air line, it provides absolute lubrication regardless of cycle frequency, and is adaptable to right- or left-hand mounting without modification. (Gits Bros. Mfg. Co., LE-11/4, 1866 S. Kilbourn Ave., Chicago 23, Ill.)

Variable Delivery Gear Pump. Designed upon an entirely new working principle, a new variable gear pump has been introduced that can be adjusted to deliver lubricant at any rate from 3½ to 10½ gallons per hour. Rate of flow can be controlled by hand while the pump is in operation

(Continued on Page 276)

Atoms Trace The Wear

by W. R. Miller & H. R. Jackson*

A description of the radioactive tracer technique for measuring engine wear is given for the benefit of those not familiar with this new tool. The personnel, equipment, and safety requirements are discussed. In addition, both laboratory and field test results using the tracer method are highlighted. Corrosive, abrasive, and friction wear are covered. It is concluded that corrosive wear accounts for three-fourths of the total wear occurring in passenger cars.

Everyone is familiar with wear in one form or other. Everyone is aware that certain conditions tend to accelerate wear and are to be avoided, if possible. The housewife realizes that Johnnie's shoes will last longer if not abused and this same line of thought can be applied to the family car. There are particular engine operating conditions which, although not considered abusive, have a tendency to promote high wear. It is important that these conditions be recognized and either eliminated or, if this is not practical, alleviated by the use of proper fuels and lubricants so as to prolong the useful life of the engine.

Accurate wear measurement is necessary in detecting operating conditions which cause high wear and in evaluating the effectiveness of fuels and lubricants to reduce it. Conventional wear test methods in which attempts are made to measure the change in dimension of engine parts or the amount of iron in the crankcase oil by chemical means are long, costly, and subject to certain inaccuracies. In contrast to this the radioactive tracer method, because of its sensitivity and continuous operation without engine rebuild, is shorter and cheaper with better accuracy. Because of its rapid response to change in wear rate, it is possible, using the radioactive method, to study transitory wear phenomenon which cannot be measured by conventional methods.

THE TRACER TECHNIQUE. (1) A.E.C. Requirements. Use of the tracer method for studying wear requires compliance with Atomic Energy Commission (A.E.C.) regulations covering the use of radioactive materials. In general, this means that (a) qualified personnel supervise all activities wherein hot materials are used, (b) proper safety measures be enforced to protect personnel.

(2) Personnel Requirements. Aside from providing a trained supervisor to conduct the studies, the personnel requirements for tracer work do not differ much from those of other engine laboratory projects. Operators and mechanics can be trained to respect radioactive materials and to use radiation counters. Fewer mechanics are needed for this work since the engine runs for long periods without rebuilding.

(3) Equipment Requirements. Specialized equipment is needed for tracer work. A radiation counter must be provided together with a lead shielded chamber for greater accuracy. Other necessary items are high and low range dosage meters, lead shipping containers, shielded storage facilities, and miscellaneous glassware. It is possible to begin tracer work with an expenditure of $2,000 for this equipment provided present laboratory and engine facilities are used.

(4) Safety Features. Safety is a most important factor in all radioactive work. The legal limit of radiation exposure, 300 milliroentgens per week, is set by the A.E.C. It is mandatory that this is not exceeded. Radiation dosage meters, pocket ionization chambers, and film badges are used to insure the safety of personnel. The radiation sensitive film worn by mechanics and operators is processed weekly by an outside firm and indicates the amount of radiation received by the wearer. In addition to the maximum legal dosage set by the A.E.C., the I.C.C. requires that shipments of radioactive materials do not exceed 200 milliroentgens per hour at the surface of the container. This explains the need for special lead lined shipping containers.

(5) Procedure in Applying Technique. The first step in applying the tracer method to the study of engine wear consists of sending piston rings to an A.E.C. reactor for irradiation. This process may take from 10 to 30 days, excluding shipping time, depending upon which reactor is used. On receipt of the radioactive rings, weighed filings are used to make a reference standard which is a ratio of iron content to activity. "Hot" rings are then placed on the test pistons which are installed in the engine. Special long handled tools are used by the mechan-

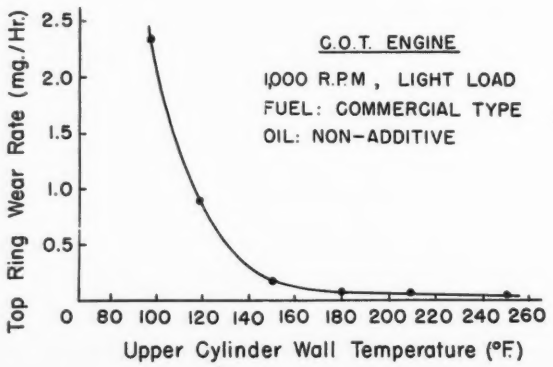

Fig. 1. Effect of cylinder wall temperature on wear.

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(This paper was co-sponsored by the ASLE Technical Committees on Bearings & Bearing Lubrication, and Lubrication Fundamentals, and presented at the ASLE 10th Annual Meeting, Chicago, April 13, 1955.)

ics to protect them from radiation exposure. The engine is then operated on a test schedule with oil samples being taken at regular intervals. The activity of the crankcase oil as measured by a radiation counter indicates the amount of radioactive iron which has worn from the ring and has been deposited in the oil. The change in activity from sample to sample is the wear rate of the engine. These data can be converted from counts per minute to milligrams of iron per hour by comparison with the standard which contains a known amount of iron.

(6) Sensitivity and Accuracy. The radioactive tracer method is an extremely sensitive tool. Wear can be measured in a matter of a few miles or a few minutes of operation. In several cases, wear was determined simultaneously by the tracer method and ring weight loss. The differences between the ring weights before and after a three month road test were compared to the total of all radioactive wear determinations made during that time. It was found that the two methods were in agreement within 10%.

The tracer method has been used to study corrosive, abrasive, and friction wear in the laboratory and in cars on the highway. These will be discussed and serve to illustrate how the method can be applied to obtain fundamental wear data.

CORROSIVE ENGINE WEAR. Various investigators experienced high wear when engines were operated with cold jackets at low speed and mild load. This kind of wear they called corrosive. Engine tests were run in our laboratory under a variety of upper cylinder wall temperatures to study corrosive wear. A Cooperative Oil Test (C.O.T.) engine equipped with a radioactive compression ring, refrigeration system, and the usual auxiliary equipment was used for this work.

A series of four hour wear tests run at various upper cylinder wall temperatures gave the data shown in Fig. 1. It can be seen that the wear was low and essentially constant from 160 F. to 250 F., but increased rapidly with decreasing cylinder wall temperature in the 100 F. to 150 F. range. These results agree quite well with other published data that show wear suddenly increasing at cylinder wall

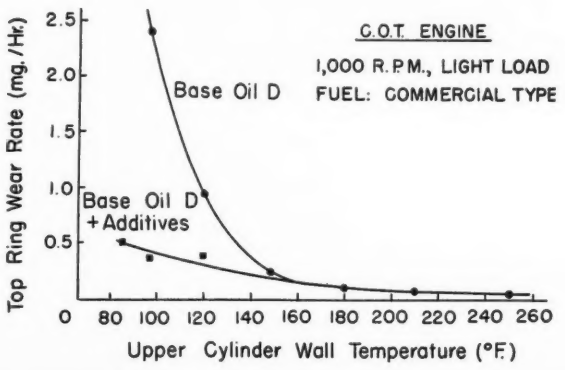

Fig. 2. Base vs. Additive oil with varying cylinder wall temperatures.

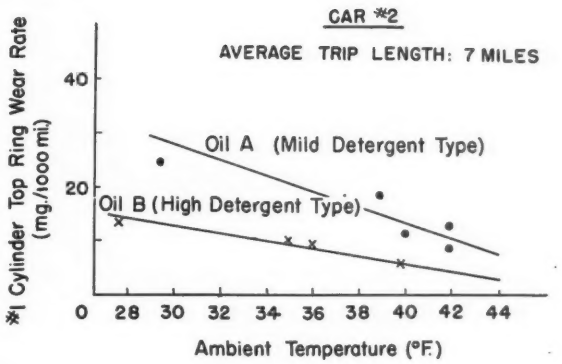

Fig. 3. Effect of alkaline detergency on wear in service passenger cars.

temperatures corresponding to the dew point temperature of the combustion gases. It appears from this that corrosive wear is caused by the action of acidic exhaust gas condensate on the piston rings and cylinder wall.

The deleterious effect of low cylinder wall temperatures on wear can be reduced by the use of properly compounded lubricants. Engine tests were run in which the oil contained an alkaline detergent additive. The effect of this oil on wear is shown in Fig. 2 where a comparison is made with the base oil wear curve. It can be seen that the two curves differ only in the range of cylinder wall temperatures where corrosive wear occurs.

A passenger car service test was run during the winter of 1950-51 in order to further study the effect of alkaline detergency on wear under cold weather operation. The cars used were employee owned and were put on test in "as found" condition except for the installation of radioactive piston rings. The cars represented various makes and ages and were driven by their owners in normal fashion. Accurate wear measurements were obtained for each week's operation. The two oils used differed in that oil "A" contained a relatively small amount of alkaline detergent while oil "B" contained a relatively large amount. The performance of these two oils is shown in Fig. 3 which contains data for only one car but which is typical of the others. The data show that higher wear was encountered during the coldest periods of operation and that a definite wear difference was obtained between the oils. This test shows that a properly compounded oil is effective in reducing engine wear.

The influence of fuel sulfur content on corrosive wear was studied by running a series of low temperature jacket tests on a Cooperative Fuel Research (C.F.R.) engine using a variety of fuels which differed in sulfur and tetraethyllead content. The data obtained from these tests, Fig. 4, show that wear is directly proportioned to sulfur content in the range of 0 to 0.25% sulfur. The results also show that from a wear standpoint the amount of sulfur in the fuel is more critical than the fuel type, sulfur source, or tetraethyllead content.

ABRASIVE WEAR. Abrasive wear is generally thought of as high wear due to the presence

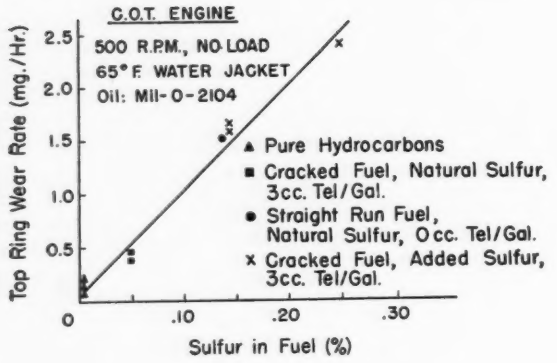

Fig. 4. Effect of fuel sulfur on low temperature wear.

of foreign particles between the piston rings and the cylinder wall. These particles may be airborne dirt, fuel and oil oxidation products, and wear debris.

It is not difficult to believe that dirty oils give more wear than clean oils; however, the relative significance of oil mileage and filtering are not generally known. To study these factors samples of used oils were obtained from cars operated in normal service. The test samples were obtained at 1000 mile intervals from cars, some of which were operated with, and some without, filters. The oils were run in a C.O.T. engine under hot cylinder wall conditions to minimize corrosive wear. (Note Table I for the data obtained.)

This shows that the wear rate increases with increased oil mileage and that there is a wear reduction due to use of filters of about 30%. The clean unused oil result is included for comparison only. If this oil had been in the engine for only a few minutes it would have picked up considerable abrasives and given a higher wear rate. Emission spectograph data show that the unfiltered oils contained greater amounts of insoluble material than the filtered oils.

FRICTION WEAR. Wear which is due to lack of sufficient lubrication and which occurs in the absence of corrosion or abrasion is called friction wear. It may be due to unusual operating conditions such as detonation and very high loads or to improper choice of oils.

The effect of detonation on wear was studied by running a C.O.T. engine under hot jacket conditions while varying the octane number of the fuel to obtain knock. As shown in Fig. 5 even trace

Table I. Effect of oil mileage and filtering on wear.

Mileage	Engine Wear (mg/hr) Filtered	Unfiltered
0 (clean oil)	.01	
1000	.22	.28
2000	.28	.35
3000	.33	.52

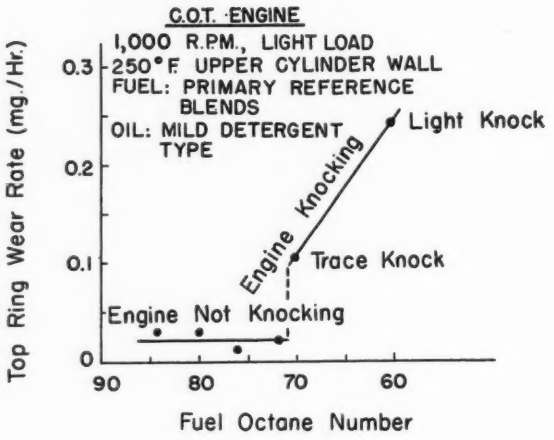

Fig. 5. Effect of knock on wear.

knock greatly increases top ring wear. The dotted portion of the curve is the authors' interpretation of the manner in which wear increases when going from nonknocking to knocking operation. Further work has shown that where periodic knock is present high wear continues for some time after the knock has subsided due to the scuffed condition of the piston rings and cylinder wall.

The effect of knock on wear under service conditions was studied by installing radioactive piston rings in two cars and driving them in a controlled road test. By adjusting the octane number of the fuel, one car at a time was made to operate with trace knock for a period of three weeks. The wear measurements made during the six weeks test showed that trace knock increases wear approximately 20% compared to knock free operation. From this it appears that knock in an automotive engine is more harmful than generally supposed.

The effect of oil volatility on engine wear was studied by adding low volatility components to Arctic oils and running them in a C.O.T. engine under hot jacket conditions. Arctic oils were used because of their tendency to give high oil consumption and high wear especially in multi-cylinder diesel engines. The radioactive wear results show that Arctic oils themselves give much higher wear than either conventional S.A.E. 10 or 30 oils. This is believed to result from vaporization of the oil film from the cylinder walls. The addition of 15% bright stock or certain chemically active anti-scuff agents reduced the wear to normal levels. Table II shows

Table II. Effect of oil volatility on wear.

Oil	% Vaporized at 10 mm & 500 F.	Relative Wear, %
SAE 10	40%	100%
Arctic Oil (Mil 10295)	95%	1000%
Arctic Oil plus 15% Bright Stock	80%	200%

the relationship between volatility and wear for some of these oils. These results were confirmed in a full scale diesel engine by another investigator.

RELATIVE IMPORTANCE OF CORROSIVE, ABRASIVE AND FRICTION WEAR. We have given specific examples of engine wear resulting from corrosion, abrasion and friction. Which kind of wear is of most importance in passenger cars? The answer to this question can best be obtained, perhaps, by examining data obtained from a road test currently being run at our laboratory.

This rather extensive program consists of twelve cars driven by employees. These cars are used as the family car and, as such, represent typical driving. They are all equipped with oil filters changed every 5000 miles. This test has been running for about two years. Through the use of radioactive piston rings, the wear rate of each individual car has been followed. An analysis of the wear pattern in these cars indicates that corrosive wear accounts for about three-fourths of the total wear, abrasion and friction making up the remainder.

SUMMARY. The radioactive piston ring technique is a new tool for measuring engine wear. It is relatively inexpensive, and presents no health or safety hazards that are difficult to overcome. Through its speed and accuracy we have been better able to understand the various causes of engine wear, and their relative importance in limiting the useful life of engines. Information such as this is of much value in guiding the course of future fuel and lubricant improvements.

Personals

O. L. Maag (ASLE Past-President), internationally known lubrication engineer, has become associated with The Ironsides Co., lubrication specialists of Columbus, Ohio, and Liverpool, England, as Consultant. (Recently retired as Research Chemist and Chief Lubrication Engineer of Timken Roller Bearing Co., Mr. Maag is credited with many major improvements in industrial lubrication techniques; among these is the Timken Lubricant Tester which measures the load-carrying ability of bearing and gear lubricants. This device aided greatly in the development of extreme pressure lubricants which make possible today's high speed mills.) Author of many articles as well as a lecturer on lubrication, Mr. Maag holds membership in ASLE, ACS, ASTM, SAE, and the American Association for the Advancement of Science.

J. W. Hopkinson (ASLE President), Penn-Petroleum Corp., is recuperating at his home in Detroit after an illness which hospitalized him late this Spring.

P. M. Ruedrich (Past-Chairman of ASLE Northern California Section), Griffin Chemical Co., has been appointed by **Prof. L. M. Tichvinsky**, Universiy of California, to act as Representative of the San Francisco Chapter of the Engineering Societies Personnel Service Advisory Committee.

Newly-elected Officers of the National Society of Professional Engineers include: **A. C. Neff** (Armco Drainage & Metal Products, Inc.), as President; **L. F. Frazza** (Johns-Manville Sales Corp.), **W. Howe** (Gardner & Howe, Inc.), **R. J. Rhinehart** (Arkansas Power & Light Co.), **L. R. Durkee** (Seattle Housing & Home Finance Agency), **G. H. Dyer** (Independence Div. of Missouri Water Co.), and **V. E. Gunlock** (Chicago Transit Board), as Regional Vice-Presidents; with **R. B. Allen** (University of Maryland), as Treasurer.

E. E. Smith has been appointed Manager of Lubricant Development in the chemical division of Climax Molybdenum Co.

Battenfeld Grease & Oil Corp., Kansas City, Mo., has announced the following appointments: **T. N. Bath** as General Sales Manager; **C. Gore** as Sales Manager, Lubricating Grease Div.; and **R. Shepherd** as Southern Sales Representative.

J. R. McPhee, formerly Vice-President in Charge of Sales for the Palmoshield Div., has been elected Vice-President in Charge of all Sales Operations of The Ironsides Co., Columbus, Ohio.

E. C. Wahl has been named Sales Manager of the Seal Division of Gits Bros. Mfg. Co., Chicago.

H. H. Roosa, formerly Vice-President of Manzel Div. of Frontier Industries, Inc., has been appointed Vice-President in Charge of Subsidiaries of the Houdaille-Hershey Corp., Detroit, following Houdaille's recent acquisition of a group of diversified plants owned by Frontier.

W. Deutsch (ASLE Vice-President at Large), formerly Sales Manager of Trabon Engineering Corp., has been appointed Sales Manager of the Lectroetch Co., 14925 Elderwood Ave., East Cleveland, Ohio. ("Lectroetch" is a patented electrolytic process of permanently marking metals of all types, and is widely used in the machine tool, bearing, and airplane industries as well as in many others. New equipment and devices will be announced shortly which will greatly broaden their field of application and use.)

Obituary: **E. W. McClure** (ASLE Philadelphia Section), The Atlantic Refining Co., May 21.

What Happened To My Oil?

by C. W. Nichols, Jr.*

"What happened to my oil?" is a familiar question to those who are asked to view the pieces at a post mortem. Reasons for trouble in lubrication are many and not all of them are due to the lubricant. The present paper gives a new insight into this old question and the examples cited within this paper are particularly enlightening.

Every lubrication engineer has a fundamental interest in the properties of the lubricants he uses and the changes they undergo in service. During 1954 approximately 50,000,000 bbls. of lubricating oil were manufactured and sold. This represents a tremendous investment to the consumer of these products. He is naturally concerned with efficient use of them both with respect to length of service and satisfactory performance. A working knowledge of lubricant characteristics and the effect of service conditions on them is a long step towards reaching these objectives. This discussion deals with the laboratory tests used in evaluating lubricating oils. It will cover the most important phases of this from the decision to take a sample to the final analysis interpretation and its application. Most of the emphasis will be on the laboratory tests and their practical significance. No attempt will be made to cover any specific applications in the text. Detailed examples will be used as illustrations.

WHY TAKE A SAMPLE? A sample is usually taken when a problem exists or some facts need to be established. There are many different reasons why the characteristics of a lubricant might be checked, but the most important general motives are these:

(1) To establish conformance with the supplier's guaranteed characteristics.

(2) To determine suitability for continued service.

(3) To establish drain periods.

(4) To find cause for abnormal change or performance of the lubricant.

(5) To determine reasons for equipment failure.

Establishing conformance with the supplier's guaranteed characteristics is a normal, routine, precautionary measure. It is particularly important where bulk deliveries are being made into existing storage facilities. It assures the proper product is being received, preventing contamination with all the subsequent complications. In addition, knowledge of the characteristics as received provides a baseline for future comparison with the used lubricant.

*Socony Mobil Oil Co., Inc., Technical Service Dept., 412 Greenpoint Ave., Brooklyn 22, N. Y.

(This paper was presented at the ASLE New York Section Meeting of October 20, 1954.)

Sample analysis to establish suitability of a lubricant for continued service is general practice in most large installations and in many smaller critical units. Turbine generating plants, hydraulic systems, and circulating oil applications such as rolling mills are only a few examples of this. A continuous record of oil condition is maintained. Any significant change is quickly noted so that the necessary steps for correcting the situation can be taken. Where internal combustion engines are involved, periodic sampling of the crankcase oil is advisable in order to establish satisfactory drain periods.

In many cases abnormal changes noted visually or by equipment performance can be satisfactorily corrected by lubricant sampling and analysis. Rapid change in appearance, formation of sediment, temperature rise, and other operating difficulties can oftentimes be resolved by analysis of the oil. The loosening of previously formed sludges and presence of wear debris are some of the factors that can be detected in this way. Also, contaminants can be identified.

When equipment failure occurs, analysis of the lubricant involved may frequently shed light on the problem. Presence of contaminants, oil deterioration, or identification of other factors can lead to its proper solution. In many cases, incipient failure may be detected which can then be prevented by varying operating conditions, change of lubricant or even equipment overhaul.

These, in general, are the principal reasons for sampling. There are many others but they all add up to a logical adjunct to a proper maintenance program. Knowledge of the lubricants' condition is essential to adequate servicing of any equipment using them.

Table I. Schedule of tests for used oils.

Table I	Turbine & Hydraulic	Circulating	Gear	Spindle	Engine	
					Gasoline	Diesel
Gravity, °API	X	X		X		
Flash, °F.						X
Viscosity	X	X	X	X	X	X
Insolubles			X		X	X
Water	X	X	X	X	X	X
Ash			X		X	X
Neutralization No.	X	X		X		X
Color	X			X		
Dilution					X	X

HOW TO TAKE A SAMPLE. When procuring a sample, careful consideration should be given to the problem involved. When it is desired to determine suitability for continued service, it is obvious that the sample should be representative of the oil actually in the system. For this reason, it should be taken while the equipment is in operation and from a point which insures that it is representative. For example, in a turbine where a sample is desired for this purpose, it should be taken from some point where the oil is in circulation and not drained from the bottom of the sump. Where deterioration or deposit formation may be involved, the sample should be taken so that as much of this material is obtained as possible. Careful selection of the sample will make the analyst's job easier and provide a clearer answer to the problem.

After the sample is taken it should be placed in a satisfactory container. It must be borne in mind that the analysis and its interpretation are only as significant as the sample itself. Samples of grease carried in paper bags, oils in rusted or contaminated cans, or deposits in paper cups are not encouraged. Select a container which will ensure that the sample is significant and will not change in its travel. Clean cans for petroleum products are most acceptable.

Table II. Significance of changes in test results.

Table II	Reduction	Increase
Gravity	1. Admixture with more viscous grade oil 2. Oxidation 3. Insolubles	1. Admixture with less viscous grade oil 2. Fuel Dilution
Flash	1. Admixture with less viscous grade oil 2. Fuel Dilution	1. Admixture with more viscous grade oil
Viscosity	1. Admixture with less viscous grade oil 2. Fuel Dilution	1. Admixture with more viscous grade oil 2. Oxidation 3. Insolubles
Insolubles	1. Deposition in system 2. Addition of make-up	1. Increased contamination 2. Increased oxidation 3. Corrosion 4. Wear
Water	1. Settling in system 2. Evaporation	1. Contamination
Ash	1. Loss of Additive 2. Addition of make-up	1. Contamination 2. Wear 3. Corrosion
Neutralization No.	1. Addition of make-up	1. Contamination 2. Oxidation
Color	1. Addition of make-up	1. Contamination 2. Insolubles 3. Oxidation
Dilution	1. Addition of make-up 2. Mechanical Correction	1. Increased fuel contamination

At this point the analyst's part must be considered. In order for him to come up with the best answer he must know the problem and the pertinent factors relating to it. Provide him with all the operating data possible and explain the problem so that it can be integrated with the information obtained in the inspection. In this way, the maximum benefit will be obtained from the work done on the problem.

At the risk of belaboring the point, it must be emphasized that the best results will be obtained by a significant sample, taken intelligently, put in a proper container, and submitted to the laboratory with the maximum amount of pertinent data and a clear explanation of the problem.

TESTS ON THE SAMPLE. When the sample is delivered to the laboratory, what happens to it? The ASTM Standards on Petroleum Products lists 25-30 different tests which can be conducted on lubricating oils. Obviously, all of these are not run on every sample. As a matter of fact, there are about nine tests which are used most frequently. These are:

Test	ASTM Designation
1. Gravity, °API	D-287-52
2. Flash Point, °F.	D-92-52
3. Viscosity	D-445-53T
4. Insolubles	D-893-52T
5. Water	—
6. Ash	—
7. Neut. No.	D-974-53T (Color Ind) D-664-52 (Potentiometer)
8. Color	D-155-45T
9. Dilution	D-322-35

For the moment, we will concern ourselves only with these. The ASTM Standards on Petroleum Products & Lubricants covers in detail the procedures for carrying out these tests. The lubrication engineer is primarily interested in the meaning of these tests as they apply to the condition of the lubricant. Therefore, those who wish to become familiar with the technique of testing are referred to the ASTM Standards. The discussion here will be limited to their significance as related to product characteristics.

Gravity. This is a numerical value which is an index of the weight of a measured volume of product. It is related to Specific Gravity by the formula:

$$\text{Degrees API} = \frac{141.5}{\text{Specific Gravity } 60/60 \text{ F.}} - 131.5$$

The most elementary mathematician will observe that as the Specific Gravity increases, the API Gravity will decrease and vice-versa. In other words, the lighter (in weight) a product, the higher its API Gravity.

This test is most significant in identification of an oil. Considering oils of equivalent viscosity, naphthenic types will have low API Gravity and paraffinic will have high. Its most important use for new oils is in determining weight for blending or transportation purposes. For used oils, it is helpful in detecting contamination with other grades or types of oils. Oxidation of a lubricant will

usually result in a lower API Gravity. The magnitude of this change will be dependent on the degree and type of oxidation, but it is not an accurate index of it.

Flash Point. This is defined as the temperature at which an oil gives off sufficient vapor to form an inflammable mixture with air. It is used primarily to identify and classify different lubricating oil fractions. Its greatest value is to the refiner for quality control. In used oils, it is most significant in detecting dilution or contamination with lighter products such as gasoline and diesel fuel. However, it can not be conveniently used as a quantitative measure.

Viscosity. This is the most important single characteristic of a lubricating oil. It is defined as a measure of its resistance to flow. In a bearing operating properly, the viscosity of the oil at operating temperature determines the bearing friction, heat generated, and rate of flow of oil under given conditions of load, speed, and bearing design. The oil should be viscous enough to maintain a fluid film yet sufficiently light to avoid unnecessary friction and heat generation. Viscosity changes markedly with temperature, the amount depending on the type and composition of the oil. Viscosity index is an empirical measure of the effect of temperature on viscosity. Oils with high viscosity indices (VI) are affected less by temperature changes than those having low VI.

Example 1	New Oil	Sample A 60,000 K.W. Turbine	Sample B 115,000 K.W. Turbine
Gravity, °API	31.0	30.4	28.4
Visc. @ 100 F., SSU	150	159	180
Color	1	5(Cloudy)	3
Neut. No.	0.02	0.62	0.05
Sediment, %	Nil	0.20 Largely oil oxy-products, some iron rust	Trace
Water, %	Nil	0.10(Fresh)	Nil

Example 1. Used turbine oil analysis. (Reason for analysis: periodic check on oil condition.)

Sample A. This oil is cloudy in appearance due to appreciable contamination with water and sediment. Neutralization number is at a moderate level indicating some internal change has occurred in the oil. Viscosity has increased accordingly. Any water present in the oil is considered detrimental since it may result in the formation of stable emulsions, rust and hasten oil oxidation. The source for leakage should be investigated and the condition corrected. The sediment shows the presence of oil oxy-products and rust. Except for the water and sediment, which should be removed, this oil is in satisfactory condition and, with the aid of proper purification, it may be continued in service.

Sample B. This oil has a lower gravity, higher viscosity, and darker color than the new product. Based on these results, we might say that deterioration has occurred. However, we note that the neutralization number increase is insignificant and sediment is negligible. Our conclusion, therefore, is that contamination with a more viscous grade product has taken place.

Viscosity is the refiner's main guide in preparation of a lubricating oil with respect to physical properties. His manufacturing controls are set up with minimum and maximum limits in various viscosity grades. These grades cover a wide range from light spindle oils to heavy gear oils.

In evaluating used oils, viscosity is a most significant factor. Change in viscosity may indicate dilution, contamination, oxidation, or a combination of these. Excessive variations may require renewing the oil in order that proper operation of equipment is maintained.

Insolubles. This test, run only on used lubricating oils, indicates the amount of suspended contaminants or oxidation products present. Normal pentane is mixed with the oil and the resultant insoluble material is removed by centrifuging. This precipitate is then weighed as pentane insolubles and includes oil oxidation products, soaps, resins, as well as carbonaceous, metallic and inorganic contaminants. It may then be washed with benzene which dissolves oil oxy-products, soaps, and resins. The remaining is determined as benzene insolubles. This contains the carbonaceous material, wear debris, and inorganic impurities.

Oil oxy-products, for the most part, are soluble in benzene and generally can be measured as the difference between pentane insolubles and the benzene insolubles. Ofttimes, however, they may also be found in the benzene insolubles. The solubility of these products is often governed by the type of oxidation products formed and the degree of oxidation.

A refinement of this procedure has been found very effective at the author's laboratory. Examination of the insolubles under a microscope is sometimes extremely enlightening. Often a better knowledge of the chemical nature of oil oxidation products results. In addition, the types of inorganic and carbonaceous materials can be identified. Metallic wear, corrosion products and contaminants such as dirt can be definitely isolated. Information of this type is extremely important in the final interpreta-

Example 2	New Oil	Used Oil (Approx. 6 yrs. service)
Visc. @ 210 F., SSU	105	122
% Insolubles in Benzol	Nil	0.08
% Water	Nil	Nil
% Ash	2.00	1.96
In Ash (Spectrographic)		
Major	Additives	Additives
Minor	-	-

Example 2. Used gear oil. Viscosity of this product has increased to the next viscosity grade due to prolonged service. However, the oil is relatively free of local contaminants as indicated by the absence of water and low insolubles content. Analysis of the ash shows compounding materials are at normal levels. No evidence of gear wear is noted in this sample. In order to restore this product to its original viscosity, less viscous gear oil of the same quality can be added as make-up. The amount required can be determined from viscosity blending charts.

tion of the analysis.

In evaluating "insolubles", we must consider not only the total amounts and the relationship between them but also any information available as to their composition. These data, correlated with other tests, will give us a fairly good picture of the condition of the oil.

Water. Water is quantitatively determined by distillation or centrifuging but can be qualitatively detected by dropping the lubricant on a hot plate. Spattering usually indicates its presence. It is detrimental to lubricating oil performance with respect to film strength, corrosion, and chemical stability. When possible, it should be removed from the system.

Ash. This test indicates the amount of metallic constituents and other inorganic materials such as dirt (silica) in the oil. These metals may derive from detergent additives, oxidation products, corrosion, wear or contamination. It is particularly important to know the ash content of the new oil when evaluating the results of this test.

Identification of metals in the ash is of considerable significance. Appreciable amounts of bearing metals may indicate corrosive action or abnormal wear. Presence of silicon in even small amounts is a danger signal that wear may be imminent if not already progressing. The location of wear or corrosion may be traced to some extent by this information. Lead in diesel-engine oil samples suggests selective removal from copper lead or lead babbitt bearings. Presence of copper in hydraulic or turbine oils may indicate reaction with the oil in coolers. Aluminum may be traced to pistons. Reduction in additive content may also be indicated by this type of analysis.

Ash analysis is not necessary on all used oils since their overall condition can be evaluated by other less complicated tests. Where trouble is suspected or being investigated, however, this test is invaluable. Spectrographic examination of the ash is particularly helpful since it is accurate and rapid. Quantitative determinations of even trace amounts of metals is feasible and is often used in analysis of used crankcase oils.

Example 3	New Detergent Type	Sample A 6 Cyl-2300 Hrs.	New Non-Detergent Type	Sample B 24 Hp-2 Stroke Cyc.
Visc. @210 F.,SSU	68	68	62	59
Flash	-	-	420	380
Dilution	Nil	4.0	Nil	2-4
Neut. No.	-	-	0.05	0.56
Pentane Insolubles	Nil	1.9	Nil	0.2
Benzene Insolubles	Nil	1.7	Nil	-
Water, %	Nil	Nil	Nil	Nil
Ash, %	0.60	0.93	Nil	0.02
In Ash (Spectrographic)				
Major	Additives	Additives Lead		
Minor	-	Iron		

Example 3. Used engine oils.

Sample A. This sample has reached the limit of acceptable conditions with respect to insolubles and ash-forming contents. Most of the insoluble contamination consists of lead compounds derived from the fuel and sooty matter from the combustion chamber of the engine. Some dilution with fuel is also present. Viscosity of the oil appears normal for the product. However, this is due to the compensating effect of fuel dilution and insolubles contamination. The former tends to thin the oil while the latter thickens it. Oil in the condition shown by this sample is unsatisfactory for use in an engine and its early drainage is advisable.

Sample B. Low flash point indicates that some dilution with fuel is present, reducing viscosity somewhat. From viscosity decrease, the amount of dilution is estimated at 2-4%. The results of other tests are satisfactory. Neutralization No. is within acceptable limits indicating that no excessive amount of internal change has occurred in the oil. No water is present. Insolubles and ash contents are satisfactorily low, the latter showing a small amount of iron from normal wear of engine parts. Based on these results, this oil is considered suitable for further service.

Ash analysis is not necessary on all used oils since their overall condition can be evaluated by other less complicated tests. Where trouble is suspected or being investigated, however, this test is invaluable. Spectrographic examination of the ash is particularly helpful since it is accurate and rapid. Quantitative determinations of even trace amounts of metals is feasible and is often used in analysis of used crankcase oils.

Neutralization Number. This value is defined as the weight in milligrams of potassium hydroxide required to neutralize one gram of oil. Considering non-detergent oils, this test gives useful information regarding changes in the oil caused by oxidation. This reaction is usually accompanied by a rise in neutralization number, the rate and magnitude of this increase depending on the type and composition of the lubricant. Even this statement must be qualified since some metal deactivators and oxidation inhibitors impart a high initial neutralization number. In service, this value actually may decrease gradually and then start to rise. Neutralization number can not be correlated with corrosive tendency, the latter being a function of the type of acidity and not the amount.

The significance of neutralization number for detergent oils can not be generalized at the present time. Detergent additives vary widely in their

Example 4	New Oil	Used Oil (Spindle bases-after 6 weeks service)
Gravity, °API	33.0	32.0
Visc. @ 100 F., SSU	59	60
Color	1	2
Neut. No.	0.20	0.22
Sediment, %	Nil	0.05 Iron Fines, Fibers
Water, %	Nil	Trace

Example 4. Used textile spindle oil. (Reason for analysis: to establish drain and relubrication periods.) This oil contains a trace amount of water and a small amount of sediment. The water is undoubtedly due to condensation of moisture from humid atmospheres maintained at the mill. The nature and amount of the sediment in the spindle oil which was sampled at a point where impurities are concentrated, suggests minor wear and local contamination is occurring. The results of other tests are good. Accordingly, we suggest extending the drain and relubrication periods.

chemical composition. Some are acid, some basic, and others neutral. The interpretation of the neutralization number then depends on the type of additive present, its concentration, and chemical reactions in service, and the amount and type of contaminant. Modifications, refinements, and new techniques in neutralization number tests are being studied to determine their applicability to used oil evaluation. Neutralization number can not be used as a single criterion for used oil condition. It must be correlated with other characteristics for proper interpretation of its significance.

Color. Color is not a reliable basis for an opinion on used oil condition. It is particularly misleading where engine oils are concerned. Many oils such as detergent types, darken rapidly. As little as 0.1 per cent of sooty material will turn the oil black, yet lubricating value is unimpaired. In other oils, small amounts of complex color bodies may influence the appearance of this oil yet have no effect on its stability or performance. Use of other tests is much more dependable in evaluating the condition of a used oil.

Dilution. This test is used only on engine oils. For gasoline powered equipment, the conventional ASTM distillation over water is used. It indicates the amount of dilution resulting from entrance of fuel into the crankcase. For diesel units, this method is not applicable. An estimate can be made by comparing the viscosity of the used oil with that of the new oil. The viscosity of the fuel must also be known. This is obviously only an approximation but it does give a significant indication of fuel leakage.

INTERPRETATION OF RESULTS. After the results of the tests have been obtained, it is then necessary to interpret them in relation to the particular problem at hand. Obviously, all these tests are not run on every sample. They must be selected in accordance with the type of oil, application, and the information desired. Referring back to the five principal reasons for sampling, the problem of establishing conformance with the supplier's guaranteed characteristics is fairly straight forward since the selection of tests is already obvious. Let us consider the suitability of an oil for continued service.

Shown in Table I is the normal schedule of tests for several different oil classifications. In many cases, not every one indicated is run. For example, a sample of turbine oil visually inspected and seen to be clear and bright, will not be subjected to an insolubles examination. In others, one test such as viscosity or water will give the required information. Some samples represent problems which require much more extensive testing. It may be necessary to use X-ray diffraction equipment to definitely identify a contaminant or special chemical tests to establish the presence of additives. For the most part, however, the schedule shown will give sufficient information to establish the condition of an oil in service.

Interpretation of these results requires consideration of the changes in the test values, either compared to new oil or to previous analyses from the same equipment. Table II gives a brief summary of what the variations may indicate. These comments assume that no purification or reclamation treatment has been used between sampling periods.

It is evident that conflicting conclusions can be drawn if our evaluation is based on the results of one test. For example, viscosity increase may indicate oxidation, but other tests show that contamina-

Example 5	New Oil	Used Oil
Visc. @ 210 F., SSU	127	138
Color	7	Gray
Neut. No.	0.7	0.7
Sediment, %	Nil	1.8
Nature	-	Largely aluminum flakes & fines
Ash, %	0.12	0.51
In Ash (Spectrographic)		
Major	Additives	Aluminum Additives
Minor		

Example 5. High temperature circulating oil. (Reason for analysis: to find cause for abnormal discoloration of product.) The abnormal discoloration of this product was due to contamination with aluminum flakes and fines. On the basis of this analysis, an investigation was conducted. The source for contamination was traced to the improper installation of aluminum bearing shields resulting in grinding of these parts and subsequent contamination of the oil with aluminum metal.

Example 6	New Oil	Used Oil As Rec'vd	Used Oil After Settling	Analysis of Separated Sediment
Gravity, °API	25.7		25.7	
Visc. @ 100 F., SSU	300		302	
Appearance	Clear	Cloudy	Clear	
Water, %	Nil	Trace	Nil	
Sediment, %	Nil	0.40	Nil	
Ash, %	Nil		Nil	68.5
In Ash (Spectrographic)				
Major	-		-	Sodium, Silicon
Water Extract		Alkaline	Neutral	Strongly Alkaline

Example 6. Used hydraulic and way lubricant. (Reason for analysis: deposition of sludge after 2 hours service-freezing of valves; equipment, surface grinder.) The sample as received was cloudy in appearance and contained a considerable amount of sediment which separated on standing. The sediment-free oil showed test properties similar to new product indicating that the oil itself was unaffected and not likely to form deposits. Analysis of the sediment indicated contamination with sodium silicate, commonly known as water glass. This material is used in cementing refractory materials and sealing cardboard cartons in addition to many other commercial uses. It is insoluble in petroleum and entirely foreign to oil. However, in water solution, it can be mistaken for oil as subsequent investigations showed.

tion is the real solution. A careful study of all the analytical data correlated with the known operating conditions is necessary for accurate interpretation. Examples 1 and 2 are typical of the problems encountered in determining the suitability of an oil for continued service.

In certain cases, it is desirable from the standpoint of operating practices to determine the length of service expected of an oil. In these cases, frequent samples are taken until a point is reached where the oil is considered unsatisfactory for further use. Consequently, after draining and refilling, the oil is allowed to remain in service for the estimated correct period. Cases of this type are represented by installations containing small volumes of oil such as automotive gasoline engines, fork trucks, and similar equipment. This practice establishes a normal drain period and eliminates the necessity for frequent Lab examination. Examples 3 and 4 typify this kind of sample.

As mentioned previously, instances do occur where performance of the product is not up to the expected standard. This may be indicated by abnormal viscosity increase, unusual change in color, rapid formation of deposits or changes in operating conditions. Frequently, analysis of the oil can throw considerable light on the difficulty. We may find evidence of contamination or unusual temperature conditions that will account for the poor performance of the lubricant. A careful investigation must be made in order that the normal service life of the lubricant and equipment be realized. Examples 5, 6, and 7 show information which can be derived by analysis of the oil in cases of this type.

Finally our last type of problem involves investigation of equipment failures. This sort of problem can cover a tremendous range of troubles. Very often analysis of the oil will serve only to exonerate the lubricant from blame. There are many instances, however, where valuable information can be obtained. This may lead to necessary changes in operating procedures, maintenance, or housekeeping. Example 8 for instance indicates leakage of contaminant from some other phase of the operation which led to valve sticking. Example 9 is one in which materials with highly catalytic tendencies entered the oil system. Correction of this involved redesigning of the process.

Example 7	New Oil	Used Oil
Viscosity @ 200 F., SSU	54	59
Dilution	Nil	2.8
Pentane Insolubles	Nil	1.2
Benzene Insolubles	Nil	1.0
Water, %	Nil	1.1
Ash, %	0.62	0.77
In Ash (Spectrographic)		
Major	Additives	Additives
Minor		Lead, Sodium, Chromium, Iron

Example 7. Used automotive engine oil. (Reason for analysis: poor performance of product, tendency to sludge; equipment, 6 Cyl, 700 hrs. service.) This sample of oil is found to contain an excessive amount of water causing the formation of emulsion sludge. Sodium and chromium found as minor constituents in the ash residue are related to water conditioners. Their presence in the oil suggests cooling system leaks. Since this may result in bearing failures or other harm to the engine, the source for leakage should be investigated and the condition corrected. Results of other tests are satisfactory.

Example 8 Description of Deposit	Black, Soft, Crumbly Material
% Oil	30.7
% Soaps, Oxidized Oil	19.9
% Carbonaceous, Metallic	49.4
	100.0%
Nature - Micro Exam	
1. Iron Fines	Small Portion
2. Mineral Matter	Moderate Portion
3. Water Soluble Material	Large Portion
a. Alkalinity	Strong
b. Carbonates	Present
% Ash	35.6
In Ash (Spectrographic)	
Major	Sodium, Silicon
Minor	Aluminum, Iron, Potassium

Example 8. Gas compressor deposit. (Reason for analysis: valve sticking, piston-type; source of sample, scraped off gas-and-air mixing valve.) From inspection it appeared that water soluble, alkaline carbonates were primarily responsible for deposit build-up and sticking of valves. Why such material should be present was not clear. Alkaline cleaners may have been used on the equipment. Other mineral matter, the probable source of the aluminum and silicon, may have been from dirt carried in with gas or air. The iron probably represented wear particles. The soaps and oxidized oil, probably derived from lube oil and gas processed, likely act as a binder for the inorganic matter in building up the deposit.

Example 9 Description	Brown Sludge
% Oil	88.2
% Soaps - Oxidized Oil	10.7
% Carbonaceous, Metallic, Etc.	1.1
	100.0%
% Ash	2.6
In Ash (Spectrographic)	
Major	Iron
Minor	-
% Nitrogen	
In Original Sample	0.69
In Soaps & Oxidized Oil Portion	5.31

Example 9. Vacuum pump failures. (Reason for analysis: sludging of oil, failure of pumps; operation, evacuating equipment.) Analysis of this sample showed it to be composed principally of oil thickened by oxidized materials. Large concentrations of nitrogen compounds were found in this oxidized portion, indicating that nitrogenous gases such as nitrogen dioxide were being drawn through the pump. Gases of this type are extremely active in the deterioration of petroleum oils and result in harmful sludge. Subsequent investigation showed part of the process involved chemical treatment. Decomposition of these chemicals occurred during evacuation resulting in active gases drawn through the pump. The oil in the vacuum pumps was exposed to these gases, resulting in sludge and failure of equipment.

CONCLUSION. It should be evident from the foregoing discussion and examples that finding out what happened to an oil is not always a simple problem. Certain basic test data must be obtained, sometimes supported by more extensive examination. The final conclusion is reached by proper cooperation of plant personnel, service engineers and the laboratory. For the most efficient use of these men there must be: (1) An accurate appraisal of the problem; (2) A truly representative sample; (3) Significant information on operating data and service conditions; (4) Careful laboratory analysis; (5) Interpretation of the data by an experienced technical staff.

Book Reviews

Practical Lubrication, Vol. 1, by A. S. Morrow, et al. American Society of Lubrication Engineers, Chicago, 1954, 46 pages, price $1.00. (Reviewed by K. H. Strauss, The Texas Co.)

This publication is a compilation of practical articles covering the solution of lubrication problems in industry.

"Cleaning Lubrication Systems," by A. S. Morrow, describes how both new and in-service oil systems of all types should be cleaned to obtain the maximum life from the new charge of oil. Various flushing oils and their characteristics are mentioned. Some of the systems included in the article are steam turbines, hydraulic systems, internal combustion engines, and heat exchange systems.

"Coal Mine Lubrication," by C. W. Thompson, discusses the proper type of lubricant to be used in the large variety of equipment used in mining. Both oil and grease requirements are mentioned.

"Grease Lubrication Of Ball Bearings," by L. D. Cobb, gives a description of seal design and its effect on grease performance. Various tests which evaluate grease performance in ball bearings are shown including the use of radioactive tracers to "tag" grease flow. A brief discussion of synthetic grease is also included.

"Lubricating Greases," by J. L. Finkelmann, is a good summary of grease composition and manufacture. Different metal soap bases and their applications are listed as well as the function of coupling agents, inhibitors, and other additives. Generally used methods of manufacture of greases are covered. The article concludes with a discussion of future trends in grease lubrication.

"Lubrication Requirements Of Gears As Seen By A Gear Engineer," by J. L. Collins, mentions the effects of numerous gear variables such as tooth spacing, surface finish, tooth modification, sliding velocity, abrasive wear, and others. Solutions to many of these problems are also given.

"Open Gear Lubrication," by H. W. Winkler, supplies considerable information in a field where such information is not usually readily available. Different types of lubricants along with their advantages and applications are described for all types of open gears.

"Planned Lubrication As A Part Of Plant Maintenance," by T. R. Witt, outlines a planned lubrication program which eliminates or minimizes many of the maintenance problems caused by unsystematic lubrication procedures. Typical lubrication check charts are shown, the organization of a planned program is described, and the savings realized from such a program are indicated.

"Reduction Of Gear Failures," by S. D. Craine, covers in detail the causes and remedies for different types of gear failures. Descriptions which will lead to the identification of these failures are given.

"Seals & Closures," by E. W. Fisher, covers the field of contact and non-contact seals. Descriptions of various seal types are given and their functions are explained. Different seal materials and the effects of lubricants on these materials are discussed.

"Steel Mill Lubrication From Management's Point Of View," by T. R. Moxley, indicates the importance attached by management to planned lubrication systems in furthering more efficient operation. Comparative maintenance and lubrication costs are shown for the author's company.

Coming Events

SEPTEMBER, 6-16, National Machine Tool Builders Association (Production Engineering & Machine Tool Shows), Navy Pier & International Amphitheatre, Chicago, Ill.

12-15, Society of Automotive Engineers (50th Annual Tractor Meeting & Production Forum), Hotel Schroeder, Milwaukee, Wisc.

12-16, American Society of Mechanical Engineers (Joint IRD-ISA Conference), Shrine Auditorium, Los Angeles, Calif.

19-22, American Institute of Mining & Metallurgical Engineers (AIME, Industrial Minerals Div., fall meeting), Asheville, N. C.

25-28, American Society of Chemical Engineers (National Meeting), Lake Placid Club, Lake Placid, N. Y.

25-28, American Society of Mechanical Engineers (Petroleum Conference), Hotel Roosevelt, New Orleans, La.

26-29, Association of Iron & Steel Engineers (Convention), Hotel Sherman, Chicago, Ill.

OCTOBER, 31 thru Nov. 2, National Lubricating Grease Institute (Annual Meeting), Edgewater Beach Hotel, Chicago, Ill.

10-12, ASLE-ASME 2nd Annual Lubrication Research Conference, Hotel Antlers, Indianapolis, Ind.

11-15, Society of Automotive Engineers (50th Annual Aeronautic Meeting), Hotel Statler, Los Angeles, Calif.

Significance Of Viscosity Studies Of Fluid Lubricants At High Pressures

by L. B. Sargent, Jr.*

The various investigations concerning the effects of high pressures upon the viscosities of fluid lubricants are briefly reviewed. Representative data from the literature are presented to illustrate the differences in the high pressure-viscosity behavior of several mineral oils, fatty oils, and synthetic fluid lubricants. At a few thousand psi pressure, the degree of difference among the viscosities of lubricants is great enough to cause the generally accepted equations, used to compute viscosities in hydrostatic lubrication theory, to be in serious error. Examples are used to emphasize a need for a more correct yet practical formulation which engineers can use to describe viscosities of fluid lubricants under high pressures.

Although the knowledge that pressure causes an increase in viscosity is rather old, its use has been somewhat limited and restricted mainly to laboratory investigations. There are, in fact, very few laboratories equipped to conduct viscometric investigations at high pressures. This situation is difficult to understand in view of the urgent necessity for data of this kind for use in present-day lubrication design problems.

Viscosities of fluids at elevated pressures, as at reduced temperatures, are influenced so greatly by the chemical nature of the fluid that generalizations are most dangerous. Many engineering design equations, in which viscosity plays an important role, are so general in regard to the viscosity term that the data obtained from the use of such formulations are in gross error and are at the best poor estimates of little value. Examples of these equations are presented later in this paper. The accumulation of data, experimentally determined, concerning the actual behavior of the viscosity of fluid lubricants under pressure, will form a very important part in the supporting framework which will lift the art of lubrication to its deserved and needed status as a science. These data will then be of value in the elucidation of many phenomena in lubrication which are now only partially understood.

METHODS OF MEASURING VISCOSITY UNDER PRESSURE. In general, the techniques used in the investigation of the influence of pressure upon the viscosity of fluids are typical of those utilized in the determination of viscosity as influenced by temperature. The more common types of apparatus used in these researches include the following: (1) capillary tubes,[14] (2) ball rolling in a slanted tube,[11] (3) weight falling in a vertical tube,[3] (4) rotating cylinders.[18] The high pressure generating and measuring apparatus and techniques, developed mainly by Prof. P. W. Bridgman of Harvard, have been of the utmost importance in this field. The investigations conducted prior to a very few years ago were concerned mainly with petroleum and fatty oils.

For some time, M. D. Hersey has been collecting the published data on the viscosity of lubricating oils under pressure and reducing these data to the same units for comparative purposes. Coordination of these data has been a very active part of the program of the A.S.M.E. Special Research Committee on Lubrication. Comparison of published results on high pressure viscosity is rather difficult because of the diversity of units and graphical methods adapted for expressing the relationships.[12a]

To indicate the type of investigations conducted in this field and to illustrate the scope of this work, a few examples from the literature are presented in Table I.

The most recent work in the field of high pressure viscometry was that sponsored by the A.S.M.E. and conducted by the Harvard group. As a result of this interest, a needed impetus was supplied to the development of high pressure apparatus and techniques. Acknowledgement must also be made of the investigations conducted by E. M. Griest[10] under the sponsorship of the API wherein a miniature rolling ball viscometer was developed in order to measure the influence of pressure upon the viscosity of very small samples of rare pure organic compounds synthesized by API research teams. This work is an important step forward in an attempt to establish the inter-relationships between chemical structure of fluids and their viscosity behavior.

The apparatus currently available for use in investigating the viscosity behavior of fluids under high pressures are adequate in many respects, particularly with regard to available ranges of temperature and

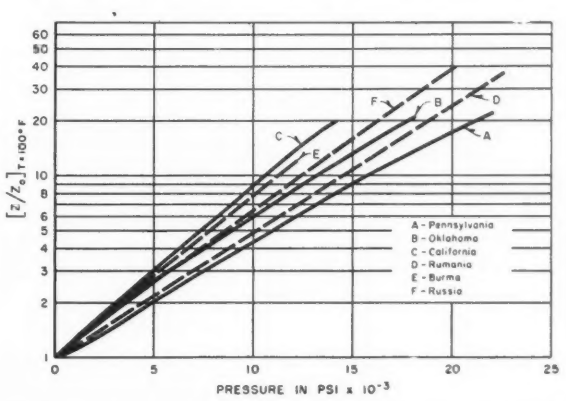

Fig. 1. Influence of pressure upon the viscosity of mineral oils from various crudes.

*Aluminum Co. of America, Research Laboratories, Freeport Rd., New Kensington, Pa.

(This paper was sponsored by the ASLE Technical Committee of Physical Properties of Lubricants, and presented at the ASLE 8th Annual Meeting, Boston, April 14, 1953.

pressure. In one very important sector of this field, however, additional development work is needed. This exception concerns apparatus useful in determining the conjoint influence of pressure and rate of shear upon the viscosity behavior of fluids. This portion of the field will be of increasing importance in the future when synthetic fluids and mixtures of synthetic and petroleum oils become of more interest and utility in industrial applications. Another important reason for this need is the ever increasing rubbing speeds (shear rates) of many machine elements which must be lubricated and/or cooled by some fluid.

EXPERIMENTAL DATA. Effect of Crude Type in Mineral Oils. The effect of pressure upon the viscosity of fluids is dependent upon several variable conditions. Limiting the discussion for the moment to mineral oils, one of the factors of importance in this regard is the type of oil. The chemical nature of the constituents of a mineral oil, i.e., the ratio of paraffinic to naphthenic compounds, etc., determines the extent of the influence of temperature and pressure upon the viscosity behavior.

Experimental evidence indicates that the viscosity of a paraffinic mineral oil is less affected by temperature changes than that of a naphthenic mineral oil. Thus a paraffinic oil is arbitrarily characterized by a high and a naphthenic oil by a low viscosity index. In the same manner, and probably for the same reason, the viscosity of a paraffinic mineral oil is less affected by pressure than the viscosity of a naphthenic mineral oil.

Dow and his students[5, 6, 8] have published the results of their investigations into the effect of crude oil type upon the pressure-viscosity relationships. The data they obtained are compared at 100 F. in Table II. The viscosity values presented in this table are in centipoises and the pressures in pounds per square inch. A more easily usable and understood method for comparison of such data consists of the use of the isothermal relative viscosity, i.e., the ratio of the viscosity, Z, at an elevated pressure, P, and some temperature, T, to the viscosity of the same fluid at atmospheric pressure and the same temperature, i.e., $(Z_p/Z_o)_T$. The relationships between pressures and the logarithm of the isothermal relative viscosities of the mineral oils described in Table II are presented in Fig. 1.

The curves presented in Fig. 1 describe the rather important differences in the manner in which the crude type influences the reaction of these materials to pressures in regard to viscosity behavior. Dow indicated the crude types of these oils as follows: Pennsylvania (paraffinic), Oklahoma (mixed naphthenic-paraffinic), and California (naphthenic). Thus the curves of Fig. 1 indicate that the foreign crudes may be typed as follows: Rumania (paraffinic), Russia (mixed naphthenic-paraffinic), and Burma (naphthenic).

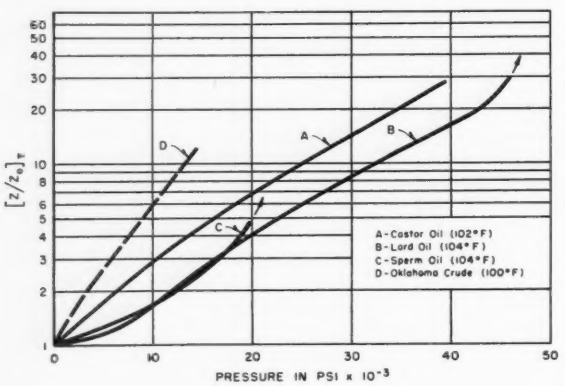

Fig. 2. Influence of pressure upon the viscosity of fatty oils.

Fatty Oils vs. Mineral Oils. The viscosity of fatty oils is, of course, influenced by temperature and pressure in a manner similar to that exhibited by mineral oils. Investigations have shown that the fatty oils as a class possess viscosities which are influenced to a lesser degree by pressure than mineral oils. In addition, fatty oils generally exhibit an apparent solidification at lower pressures than do mineral oils. These observations form the basis for a theory which supposedly accounts for the "oiliness" properties of fatty oils (as opposed to the adsorption theory).

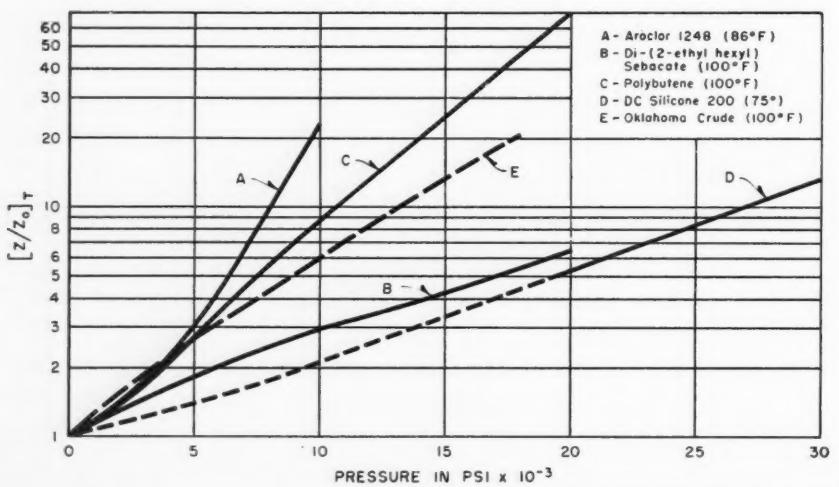

Fig. 3. Influence of pressure upon the viscosity of synthetic lubricants.

Viscosity - pressure data for some representative fatty oils were selected from the literature and are presented in Table III. The isothermal relative viscosities of these oils were calculated and are shown as Fig. 2. For comparison the isothermal relative viscosity curve for the Oklahoma base mineral oil is included. Great interest is attached to the fact that sperm oil apparently solidifies at this temperature at a much lower pressure than the other two fatty oils. As mentioned previously the fatty oils have

viscosities that are less affected by pressure than those possessed by mineral oils.

Synthetic Lubricants vs. Mineral Oils. Synthetic fluid lubricants consist of many different types. These materials have viscosity-temperature behaviors which cover and exceed in both directions the range normally exhibited by mineral oils. On the one hand, some of the silicones exhibit a VI greater than 200, and on the other, some of the fluorocarbons a VI less than —600. The normal VI range of mineral oils is of course 0 -- 100. The sensitivity of the viscosity of the synthetic fluids to pressure variations follows a pattern similar to that described above for temperature variations. Therefore, it is even more important in the field of synthetic lubricants to investigate in detail the viscosity-pressure relationships.

Although the use of synthetic fluids as lubricants is of recent origin, the published results of some investigations are available in the literature. A few of these data were collected and are exhibited as Table IV. The isothermal relative viscosities of these fluids along with that of the Oklahoma base mineral oil were calculated and plotted as Fig. 3. The Oklahoma base mineral oil is included for comparison since it represents an intermediate mixed base crude.

Of particular interest in Fig. 3 is the curve for the chlorinated diphenyl. This fluid exhibits one of the greatest increases of viscosity with pressure of any material investigated. At the other extreme is the silicone (DC 200) which exhibits an exceptionally flat pressure-viscosity curve.

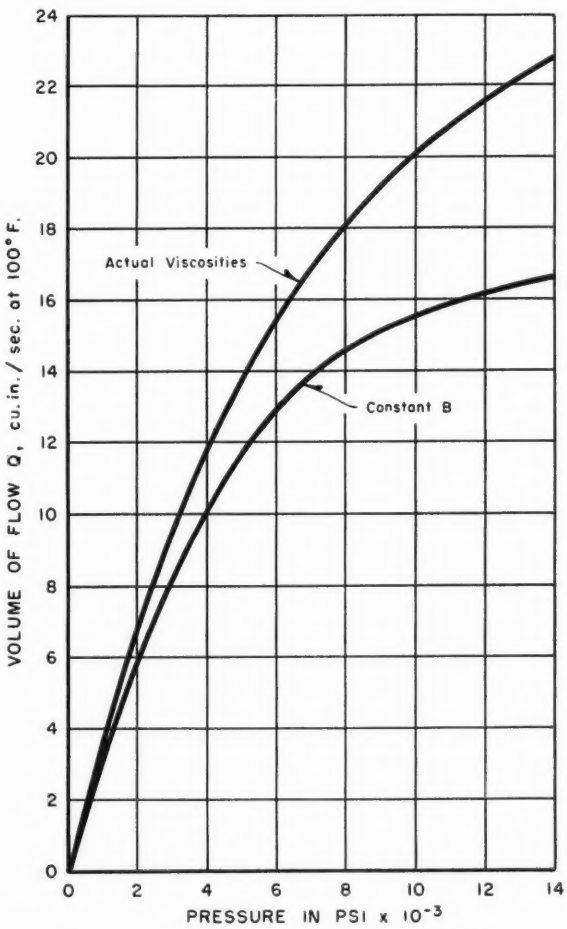

Fig. 4. Oil flow under pressure through a finite slot in a fitted bearing. (SAE 30 paraffinic oil and Eq. 3.)

Much difficulty was experienced in finding data for all fluids described at the same temperatures. The data presented were obtained at 100 F., or at that temperature closest to 100 F. that was available.

ENGINEERING ASPECTS. General. Of all the physical properties of fluid lubricants, viscosity is undoubtedly the most important. A knowledge of the viscosity behavior of the lubricant is essential for an understanding of bearing and gear lubrication and metal processing lubrication. Some of the work described here indicates that the pressure-viscosity coefficient is greater for mineral oils than for fatty oils; thus, it is to be expected that in heavily loaded bearings operating hydrodynamically, a petroleum oil will offer more friction than a fatty oil of equal viscosity at atmospheric pressure. Much work remains to be done in this field, however, before a more complete understanding of these behaviors and their degrees of importance is available.

A rather old idea in lubrication has recently become of major importance as a method of reducing friction to almost negligible values where this behavior is strongly desired. This technique has become known as hydrostatic lubrication and simply involves the application of a fluid under pressure to a recessed area in one of the rubbing surfaces. Thus a journal may be lifted out of contact with its mating bearing and provided with a lubricating film prior to the development of such a film by ordinary hydrodynamic means. Successful application of the principles of hydrostatic lubrication have been made to very slow moving heavy masses, to bearing geometries unfavorable to the development of hydrodynamic lubrication, and to a variety of moving parts where starting torque must be reduced.

Undoubtedly the most spectacular application of this technique was to the two-hundred inch telescope on Mt. Palomar in California. In this installation, a mass of about one million pounds is supported at three points by hydrostatic pads with the result that this huge structure is turned smoothly on its bearings by an exertion of only fifty foot-pounds of torque. The coefficient of friction is less than 4×10^{-6} and the power required for movement is less than that provided by the 1/12 HP clock motor installed for this purpose. The relatively low coefficient of friction provided by antifriction bearings (1×10^{-3}) would have necessitated a torque great enough to twist the frame beyond the minute tolerances allowed.

The load carrying film between the rubbing surfaces is provided by a fluid under pressure supplied by an external source, usually a pump. This pressure film will exist, unlike a hydrodynamic film, whether or not the rubbing surfaces have relative motion. The design of such devices depends upon the properties of the fluid used and the geometry of the surfaces. The basic quantities needed for design are the required pressure, film thickness, and fluid quantity.

Flow Through a Finite Slot. The basic equation used for calculating the viscous flow of an incom-

pressible fluid through a finite slot in a fitted bearing, as indicated by Prof. D. D. Fuller,[9] is

$$Q = \frac{\Delta P\, h^3 b}{12\, Z l} \qquad (1)$$

(where Q = quantity flowing in cubic inches/second; ΔP = pressure differential in pounds/square inch; h = film thickness in inches; b = slot width in inches; l = slot length in inches; Z = viscosity in reyns.) When the pressure acting on a system is more than a few hundred pounds per square inch, its effect on viscosity should be considered. The relationship between pressure and viscosity is approximately logarithmic for many fluids and has been expressed[12] by

$$Z_p = Z_o e^{BP} \qquad (2)$$

(where Z_p = viscosity at pressure P; Z_o = viscosity at atmospheric pressure; B = experimental constant; P = pressure.) Both Fuller[9] and Hersey and Shore[12] list typical values for the constant B at 100 F. as follows:

Oil	B
SAE 30 mineral oil	2.2×10^{-4}/psi
SAE 10 mineral oil	1.6×10^{-4}/psi
Castor oil	1.0×10^{-4}/psi

The constant B is actually a function of the initial slope of the curve of pressure versus logarithm of the viscosity. As illustrated in the included graphs, B is not a constant over a pressure range and is very much dependent upon the fluid under consideration. Thus a serious error may be introduced by using a value for B without due consideration being given to the variation of B with pressure and the specific fluid being considered. The importance of this situation may be emphasized by means of an example: assume $\Delta P = 5000$ psi, $h = 0.01$ inches, $b = 8$ inches, $l = 12$ inches, $Z = 100$ cp $= 145 \times 10^{-7}$ reyns at atmospheric pressure, and $T = 100$ F. Using the value of B given in this text for an oil of this viscosity and Eq. 2, the viscosity of this oil at this pressure and temperature is about 3.0 times that at atmospheric pressure. Substituting these values in Eq. 1 it is found that

$$Q = 6.37 \text{ cu.in./sec.}$$

However, the pressure gradient in an oil film must be considered when the pressure is sufficiently high to affect seriously the viscosity and thus Eq. 1 is no longer satisfactory. Under these conditions, flow must be calculated by the following:

$$Q = \frac{bh^3}{12 Z_o l}\left[\frac{1-e^{-BP}}{B}\right] \qquad (3)$$

The terms in this equation have the same meaning as those in Equations 1 and 2.

Using the above example and Eq. 3 it is found that

$$Q = 11.6 \text{ cu.in./sec.}$$

which is nearly 82% greater than the Q value obtained using Eq. 1.

However, from Fig. 1, experimental evidence indicates that an SAE 30 oil of the paraffinic type has a viscosity at 5000 psi and 100 F. which is only 2.04 times that at atmospheric pressure. Using this factor in a transposed version of Eq. 3, wherein actual viscosities rather than B is used, it is found that

$$Q = 13.7 \text{ cu.in./sec.}$$

which is about 18% greater than the Q value obtained from Eq. 3 and 115% greater than the Q value obtained from Eq. 1. Therefore, it is rather obvious that for

Table I. Representative investigations in high pressure viscometry. Key (*) : F = fatty oil; P = petroleum oil; M = miscellaneous; (**) : RB = rolling ball; C = capillary tube; FW = falling weight.

Publication Date	Number of Fluids Tested*	Temperature Range, °F.	Max. pressure, psi	Apparatus	Reference
1916	2F, 4P	Max. 275	58,000	RB**	11
1920	4F, 5P	104	18,000	C	14
1926	1F, 3P, 39M	86-167	170,000	FW	3
1928	2F, 3P	Max. 284	57,000	RB	13
1932	6F, 18P, 5M	34-313	28,000	FW	17
1937	20P	Max. 210	58,000	RB	5
1941	4F, 1P	23-69	50,000	C	16
1951	2P, 1M	32-425	150,000	FW	2

Table II. Viscosities in centipoises of uncompounded mineral oils from several types of crudes at 100 F. and various pressures.

Pressure psi	Types of Crudes					
	Burma	Russia	Rumania	Pennsylvania	Oklahoma	California
14.2	112.0	91.0	21.0	83.0	94.0	114.0
1,000		112.		91.	119.	146.
2,000	172.	133.	28.	106.	145.	183.
3,000		161.	33.	123.	175.	225.
4,000	264.	195.	39.	145.	209.	278.
5,000		255.	46.	169.	247.	346.
6,000	388.	283.	54.	198.	293.	433.
7,000		340.	63.	232.	344.	533.
8,000	584.	410.	74.	268.	405.	655.
9,000		490.	87.	310.	475.	811.
10,000	867.	590.	103.	357.	557.	995.
12,000	1300.	845.	142.	485.	775.	1540.
14,000		1210.	197.	654.	1060.	2200.
16,000		1740.	270.	850.	1430.	
18,000		2460.	370.	1100.	1940.	
20,000		3490.	509.	1420.		
22,000			703.	1830.		
Reference	6	8	8	5	5	5

precise work at pressures greater than a few thousand pounds per square inch, one must not rely upon the empirical relationships expressed by Equations 2 and 3 but should use experimentally determined values of the viscosities at the pressures of interest. The calculated deviations of these flows is shown graphically by Fig. 4 using the paraffinic oil of Fig. 1 as the basic for comparison.

Pressure Drop Through a Tube. Another relationship of importance in the design of high pressure systems is the pressure drop through a tube, which is adequately presented by the Hagen-Poiseuille Law:

$$\Delta P = \frac{8ZlQ}{\pi r^4} \qquad (4)$$

where r = inside radius of the tube and all other symbols have the same identity as before. This equation indicates that the pressure drop is directly proportional to the viscosity. Therefore, the variation in viscosity of fluids at high pressures, as shown by Figs. 1-3, are most important in this consideration.

Film Thickness in Hydrostatic Bearings. Eq. 3 indicates that the film thickness of a pressure pad in a hydrostatic system is proportional to the cube root of the viscosity or volume of flow. For these reasons the variations in viscosity of fluids at elevated pressures caused by structure and composition of the fluids will induce a variation in the film thickness of the lubricant but to a lesser degree than that indicated for volume of flow in Fig. 4.

Hydrodynamic Lubrication Theory. As in the previous sections, an equation will be used to illustrate how the effect of pressure upon viscosity influences some of the concepts in hydrodynamic theory.

Reynolds' differential equation for pressure developed in an oil film with no side leakage may be applied to the plane slider bearing with some acknowledged error because of certain necessary assumptions. The integrated form of this equation for the pressure distribution along a slider bearing is

$$p = \frac{Zv}{B}\left[\frac{6ax\,(1-x)}{(a-2a)\;(a-a+ax)^2}\right] \qquad (5)$$

(where B, a = bearing dimensions; v = velocity; a = angle of inclination; x = location in direction of motion; Z = viscosity.) Substitution of numerical values into Eq. 5 will enable one to solve for the distribution of pressure in the bearing. A curve may be drawn showing the relationship between the film pressure and the location of this pressure in the film. The area under this curve indicates the total load acting on the bearing. Thus, both the load carrying capacity of this type of bearing and the magnitudes of the pressures in the oil film are dependent directly upon the viscosity of the fluid at the operating pressure. As shown by the graphs, the viscosity is variable and dependent upon the chemical nature of the fluid. Serious errors may occur if these facts are not given adequate consideration.

The illustration used here may be applied to journal bearings with their several variations also. In addition to load carrying capacity of these bearings, the varia-

Table III. Viscosities in centipoises of fatty oils at various pressures. Key (*) : Apparent solidification occurred at or near 25,800 psi.

Pressure psi	Fatty Oils		
	Castor	Lard	Sperm
14.2	281.	26.0	28.0
2,500	373.	27.8	31.6
5,000	483.	30.2	35.6
7,500	635.	34.8	40.9
10,000	804.	42.9	47.3
12,500	1010.	54.9	56.0
15,000	1260.	68.6	70.0
17,500	1560.	85.3	92.4
20,000	1900.	105.	140.
22,500	2310.	128.	
25,000	2780.	154.	*
27,500	3370.	186.	
30,000	4020.	221.	
32,500	4780.	263.	
35,000	5700.	307.	
37,500	6910.	361.	
40,000		424.	
Temperature	102 F.	104 F.	104 F.
Reference	13	15	15

Table IV. Viscosities in centipoises of synthetic lubricants at various pressures. Key (*) : Extrapolated; (**) Aroclor 1248; (***) Dow Corning 200.

Pressure psi	Synthetic Lubricants			
	Chlorinated diphenyl**	Di-(2-ethyl hexyl)sebacate	Poly-isobutene	Sili-cone***
14.2	129.	10.0	43.0	97.
1,000	153.			
2,000	181.	12.9	59.3	110.*
3,000	223.			
4,000	287.			
5,000	384.	18.0	115.	137.*
6,000	553.			
7,000	833.	22.3	182.	161.*
8,000	1270.			
9,000	1950.			
10,000	2940.	29.0	380.	209.*
15,000		42.0	1050.	325.*
20,000		64.0	3000.	504.*
Temperature	86 F.	100 F.	100 F.	75 F.
Reference	7	2	1	4

tions mentioned likewise hold for consideration of friction force. Needless to say, the discrepancies become greater as the pressures become larger.

CONCLUSIONS. The influence of pressure upon the viscosities of fluid lubricants is a field of great importance to the science of lubrication and one which has been somewhat neglected. Information from scientifically conducted investigations is slowly accumulating to form the basis for a more lucid understanding of the role played by the various constituents of fluid lubricants in regard to pressure-viscosity phenomena.

Experimental evidence is presented that indicates the wide variation in the degree to which pressure influences the viscosities of several types of mineral oils, fatty oils, and synthetic fluid lubricants. These data are used to show the gross dependency of such important considerations in hydrostatic lubrication as flow volume, film thickness, and pressure drops through tubes upon these viscosity variations. For accurate work, the linear logarithmic relationship of the relative viscosities at high pressures (Eq. 2) is not reliable and the actual viscosity-pressure data must be experimentally determined.

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Section News

BOSTON, April Meeting. Plant tour of the Abrasive Division of the Norton Co., Worcester, Mass., followed by a technical session entitled "What Lubrication Means To The Designer," by J. H. Hitchcock, Chief Mechanical Engineer, Morgan Construction Co.

May. Past Chairman's Night, followed by a technical session entitled "Lubrication Behind The Iron Curtain," by Dr. H. L. Restnick. (Submitted by E. B. Harvey, Jr., former Sec'y.)

BUFFALO, May. A. Hart, Franklin Oil & Gas Co., presented a paper entitled "Rust Prevention," covering conditions causing corrosion, conditions for preventing corrosion, the theory of corrosion prevention through the use of rust preventives, and the selection of rust preventives. (Submitted by L. E. Locke, Jr., Sec'y.)

CHICAGO, May. E. W. Brennan, a group leader in charge of development work on crankcase lubricants, inhibited industrial oils, and greases for The Pure Oil Co., presented a paper entitled "Hydraulic Oils," discussing the desirable properties of hydraulic oils, the methods of determining these properties, and the methods of keeping these properties in the oil.

June. Annual Golf Tournament at the Cog Hill Country Club, with 51 members and guests participating. (Submitted by A. B. Wilder, Vice-Chrmn.)

CONNECTICUT, June. Election of Officers (see ASLE Directory.)

FORT WAYNE, May. Dinner meeting, followed by a color film entitled "Mexican Road Race." (Submitted by J. W. Buckner, Chrmn.)

MILWAUKEE, June. Ladies' Night, with a tour of the Miller Brewing Co., followed by a talk entitled "Exploiting the Swindlers," by Z. LeTellier, Vice-President of the Pate Oil Co.

NEW YORK, May. Panel on "Plant & Automotive Lubrication," with panel members including C. G. Hollister (Bakelite Co.), H. E. Berry (Norma-Hoffman Bearing Co.), O. W. Wuerz (Cab Service & Parts Corp., and R. K. Tonning (American Can Co.); with T. L. Brennan (Gulf Oil Corp.), as Moderator.

June. Election of Officers (see ASLE Directory. Submitted by E. Landau, Publicity Chrmn.)

N. CALIFORNIA, June. 3rd Annual Dinner Dance held at the Commissioned Officers' Mess, U. S. Naval Station, Treasure Island.

PITTSBURGH, May. Election of Officers (see ASLE Directory), followed by a paper entitled "Viscosity Classification Systems," by Dr. H. E. Mahncke, Westinghouse Research Labs., who reviewed

(Continued on Page 276)

Evaluating Bearing Materials Under Boundary Lubrication

by Dr. B. Lunn*

To work smoothly a journal bearing should be lined with a suitable bearing metal and lubricated with a suitable lubricant. If either of these factors is neglected the performance of the bearing may be unsatisfactory. This double requirement is often overlooked by bearing metallurgists and lubrication technologists.

For many years the metallurgists have explained the special functions of the bearing metals with the "duplex structure theory." This theory says that hard crystals carry the load while a soft matrix formed a plastic foundation for the load-carrying crystals. This theory is generally abandoned by modern bearing metallurgists as it cannot explain why some bearing metals are inferior to others—and that some, being almost homogeneous, are superior to the more hetergeneous alloys.

The tests described in this paper show that the ability of the metal to develop a non-scoring, boundary film is a most important property of a bearing metal.

That boundary films are formed by the lubricacants on sliding surfaces has for some years been recognized by most lubrication technologists, but it is a new concept to the metallurgists. Stated simply, bearing properties of metals depend upon the ability of the metals to react with the lubricant and the atmosphere to produce adhering boundary films. These films separate sliding surfaces and form a foundation for the full fluid film in the bearing. So much evidence has been collected in the laboratory at the Technical University in Copenhagen on this hypothesis of bearing function that we feel justified to call it a new bearing theory.

Being a metallurgist, I am deeply disappointed being unable to predict bearing metal behavior by the usual metallurgical testing methods. The tests have convinced me of the necessity to include the lubricants in our efforts to explain the performance of the bearing metals.

General Requirements for Testing Bearing Metals. In considering the requirements of bearing materials it must be admitted that mechanical properties (softness, ductility, fatigue durability, etc.) are subordinate to surface properties, and whatever is lacking in mechanical properties can frequently be supplied by suitable construction of the bearing. It is the surface properties of the sliding elements that are most decisive, and of these the most important in practice is undoubtedly the ability to resist scoring under lubrication.

If it is intended to make a comparative examination of bearing materials, the comparison should be carried out with lubrication so that a useful evaluation will be obtained. Specifically, examinations should be made in the region of boundary lubrication; it is primarily under this condition that the surface properties of the metals are of importance. The examinations ought also to be made under extreme conditions of high pressure, high speed, and the like. Higher temperatures may also be desirable.

The onset of scoring may be detected by measuring the degree of metallic contact between sliding surfaces. This may be done by electrical means. Low voltage should be used in order to avoid dielectric breakdown of the very thin lubricating film. If electrically insulating wear products are formed, the electric measurements may give a false picture of the non-scoring properties. Likewise the electric measuring methods cannot be used to study the lubricating film if conductive wear particles are formed.

A New Test Apparatus. Considerations such as these led to the development of a new bearing material test apparatus which is quite different from those heretofore used for examining bearing materials.[1] The apparatus (Fig. 1) was first described by Kauppi & Pederson[2] who used it for wear experiments with silicones.

Instead of using the usual rotating movement in a cylindrical bearing, reciprocating movement is used on a plane test specimen of the metal to be examined. The sliding element is a sphere, normally a ball-bearing ball fixed in a chuck and pressed against the test piece with a load of up to 5 kg (11 lbs.). The whole assembly is submerged in a bath of oil. The test piece measuring 6½ x 2½ x ¼" is usually made by casting and planing. The stroke is 127 mm (about 5"), and the speed of the connecting rod is 72 rpm, giving a maximum surface velocity of about 100 ft./min. By using reciprocating movement, 144 complete starts and stops are obtained per minute, and by using a fixed ⅜" ball as the sliding element with a constant load, a track is formed in the test piece with a pressure which in the beginning is equal to the compressive yield stress of the test material. The method is, therefore, primarily based on extreme pressure and controlled boundary lubrication, while the maximum speed is low.

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Electrical Contact Measurements. To follow the scoring between the sliding ball and the test piece, the contact point has imposed on it a potential of 20 millivolts obtained from a 2-volt battery over a voltage divider set at 1:100. To facilitate estimation of the resistance, the voltage divider is provided with shunt resistances of 1-10-100 and 1000 ohms. The contact point is connected to the ordinate movement of a cathode-ray oscilloscope while the abscissa movement is synchronized with the reciprocating movement of the test apparatus. It is also connected to a recording voltmeter (Fig. 2).

On the oscilloscope screen the development of electrical resistance in the track can be followed in all details, while the voltage-time relation shows the average condition. In testing a favorable metal-oil combination, the initial metallic contact is soon replaced by an interrupted indication due to the formation of insulating material. After a short time there is metallic contact only at the end points, where no movement occurs. With very good materials, insulating conditions can arise even at the end points after a short time (Fig. 3). For most materials the change from complete contact at the end points to interruption under movement is so quick that it is difficult to judge at what speed the formation of insulating layers begins. It is apparently considerably less than 5ft./min. In some cases, especially in testing less favorable materials, film formation sets in immediately, but the film then breaks down at higher speed before the maximum speed is reached at about the middle of the stroke. With other materials the formation of insulating material is less pronounced and there may be contact during the entire test, in which case there will be metallic pick-up on the ball.

The "L-value." In the great majority of tests equilibrium of the film is attained after 2 or 3 minutes, film formation and film destruction being in balance. The test can then be stopped. The area above the time-voltage curve recorded for 250 seconds measured as per cent of the entire area from zero to 20 millivolts is named the "L-value" (Fig. 4). This value has been found to provide a useful criterion for rating bearing materials with regard to scoring under lubrication. The advantage of this criterion is that it enables one to express the merit of a given bearing-material lubricant combination as a single reproducible designation. If the test conditions (pressure, shunt resistance, preparation of test pieces, ball material, etc.) are changed, the "L-value" will be changed. Hence, it can be used only as a comparative criterion, not as a basic factor of the materials tested.

Nature of the Film. The insulating film formed during the test on lubricated surfaces is not solid but is probably of very high viscosity or is plastic. If movement is stopped, the resistance in the contact point is reduced in a few seconds to a very low value, and upon resuming motion it rises again to the same value as before (Fig. 4). However, film formation is not a simple function of the viscosity of the lubricant. Lubricants of the same viscosity give widely different film formations when tested against the same metals. The film softens gradual-

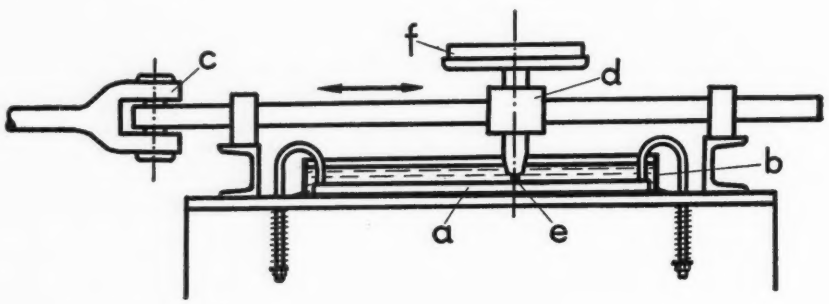

Fig. 1. Reciprocating test unit. Key: (a) Test piece; (b) Oil tray; (c) Connecting rod movement; (d) Ball chuck; (e) Sliding ball; (f) Weights.

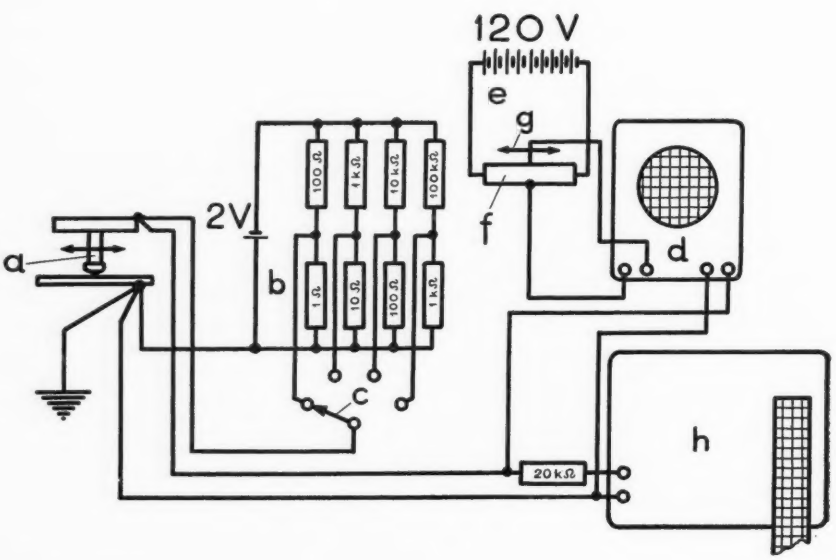

Fig. 2. Electrical measuring. Key: (a) Reciprocating ball; (b) Circuit with voltage divider; (c) Switch to obtain 0.02 V for testing the resistance conditions; (d) Cathode-ray oscillograph; (e) Synchronizing unit; (f) Carbon resistance; (g) Sliding contact fixed to reciprocating movement; (h) Recording voltmeter.

ly as the testing temperature is increased.

The film is not homogeneous; it is full of "holes" which close up as the test proceeds. It is most probably that some of the contact points in the film are due to worn off metallic particles. In testing very good bearing-metal/lubricant combinations the number of metallic contact points through the film is extremely small even after several hours' testing. Insulating wear products have not been found.

The width of the track formed in the test piece has no relation to the hardness of the bearing material. It is narrowest on the materials that give the lowest "L-values" (Table I). The wear is negligible on babbitts. The track is formed by plastic deformation in such a way that the most malleable component, the matrix, is squeezed out and forms the sides of the groove while the hard constituents accumulate in the bottom of the track. The pressure in the contact point is for white metals up to about 20,000 p.s.i.; for copper alloys up to about 55,000 p.s.i.

Correlation of Test Results with Technical Experience. Babbitts. The first tests were made with a napthenic straight mineral oil (Daminol SAE 20) taken from a single delivery. A series of tin- and lead-base babbitts were tested; the results were in good agreement with known technical experience. For example, slowly solidified coarse-grained babbitt gave much higher "L-values" (70-80%) and more scoring than did quickly solidified babbitt (20-30%) (Fig. 5). Addition of 2-3 per cent of lead to an 80-85 per cent tin-base babbitt gave lower "L-values," 20 instead of 30 per cent; this is in accord with the experience of the Scandinavian marine Diesel engine builders. Tin-base alloys with 10 per cent copper gave high "L-value" (50% instead of 30%). They are known to be less satisfactory in service. Alloys based on lead showed generally better "L-values" (10%); this is also in good accord with technical experience. Addition of iron up to 0.1% to tin alloys (80-90% tin) gave higher "L-value" (50% instead of 30%), even when the structure was very fine-grained; this is also in accord with known technical experience.

As the testing method is very sensitive, various heretofore unnoticed phenomena were found. For instance, artificial aging of quickly solidified bearing metals gave an increase in "L-value," smallest however for the high-tin alloys with a small amount of lead (Fig. 5) (Table II).

Copper Alloys. Cast brass gave heavy metallic transfer to the ball and complete contact ("L-value" 100%) — it is known to be a poor bearing metal. As to the other copper alloys, phosphorus proved to be beneficial when it was present as a phosphide eutectic. Even brass containing 0.5% of phosphorus showed improved non-scoring properties ("L-value" 25%); this is also in accord with technical experience.

Aluminum Alloys. Aluminum alloys generally gave low "L-values;" i.e., good film formation. Experience shows that many aluminum alloys can be used at low speeds, but at higher speeds they may

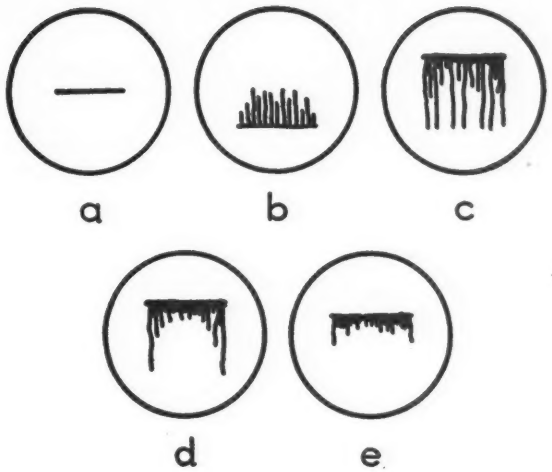

Fig. 3. Development of oscillograph picture for good white-metal/oil combination. Key: (a) Start; (b) Shortly after start; (c, d, e) Later steps of development.

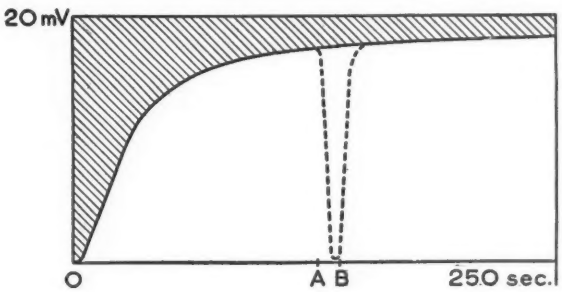

Fig. 4. Recorded curve, the "L-value." The "L-value" is the shaded area in percentage of the whole area 0.02 V in 250 sec. Interruption of movement by (A) gives decreased resistance in the point of contact. Resumed start of movement at (B) gives instant rise or resistance to former value. This indicates the plastic condition of the formed film on lubricated surfaces.

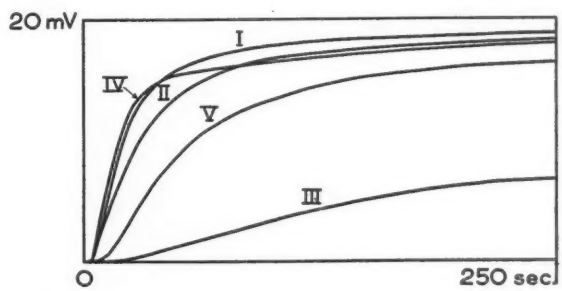

Fig. 5. Some typical recordings on white-metal tested with the same oil. Recording I, II, III obtained from alloy 83.5% Sn, 8% Sb, 6.5% Cu, 2% Pb. (I) Quickly solidified, "L": 19.5%; (II) Same artificially aged, "L": 25%; (III) Slowly solidified, "L": 75%.

Recording IV & V obtained from lead-free alloy 84% Sn, 9% Sb, 7% Cu. (IV) Quickly solidified (as I), "L": 21.5%; (V) Same, artifically aged, "L": 35%.

The samples corresponding to recording I & IV are of same hardness (H_B = 30) (5.125.30) and same size of antimony-tin cuboids (0.001" length of edge). The size of the antimony-tin cuboids in the sample corresponding to recording III is 0.005".

fail. As, however, the test is made only with relatively low maximum speed, it is in accord with this experience. Some tests were run with an alloy containing 20% Sn developed by the "Fulmer Research Institute" in collaboration with the "Tin Research Institute."[3] It gave good film formation with a common hardened ball-bearing ball as well as with a ball of 0.30% C-steel. Against the common aluminum alloys the last mentioned ball gave no film formation, but massive metallic transfer.

Cast Iron. For testing steel and cast iron, ordinary ball-bearing balls cannot be used; they are worn too quickly, and their hardened structure is annealed in the contact point. Only balls of sintered carbides have been used on such tests. Cast iron with common lubricating oil gives a considerable film formation under all conditions. A test without oil shows film formation on a test piece which is known to be wear-resistant, while a less wear-resistant cast iron gives little or no film. The appearance of the tracks is widely different: on the wear-resistant sample the track is shining, narrow, and like a thick pencil stroke. On the less wear-resistant sample the track is wide, dull and surrounded by quantities of loose wear debris. It is remarkable that on the less wear-resistant cast iron it is possible to develop an insulating film if the surrounding atmosphere has over about 4 per cent water vapor.[4]

Testing of Lubricants. If a single bearing metal is used with a variety of oils, the test gives a convenient means of evaluating lubricants.

Silicones. A silicone (D.C. 200-350 Cst.) gives, in spite of the most favorable viscosity conditions and an evidently good wetability, no film on any of the metals thus far tested. It is interesting that aluminum alloy tracks made without a lubricant, or with a silicone as lubricant, show strong, Russel-effect; i.e., formation of hydrogen peroxide,[5] and 100 per cent "L-value," while tracks made with common mineral oils show no Russel-effect and low "L-value." This shows that the silicone does not prevent oxidation and, further, that the oxides formed do not prevent metallic contact. If the phosphorus-containing brass was tested with silicone, the "L-value" was 100% and considerable wear took place.

Influence of Additives. Addition of certain high-temperature anti-oxidants (of the pinene-phosphorous-pentasulfide type) to straight mineral oils gives a considerable increase of the "L-value" on both tin-base babbitts (from 25 to 50%) and lead-base babbitts (from 10 to 20%). The specific resistance of the oil is reduced by addition of such high-temperature anti-oxidants, but not to such an extent as to be recorded at the test. Addition of low-temperature anti-oxidants, such as are used in transformer oils, has no noticeable effect on "L-value." The same is true of the normal oiliness additives. However, a chlorine-base EP additive gave a noticeable film formation on brass.

Summary of Results. A general summary of the experiments with testing of white metal and lubricants is as follows:

Item A. The largest differences in "L-value" (from 10-30 to over 70%) are found between (1) Quickly and slowly solidified white metal; (2) Plain and unsuitable lubricant.

Item B. Considerable difference in "L-value" (from 20-30 to 50%) is found between (1) Good and bad white metal; (2) Plain lubricant and, for example, a lubricant containing heavy additions of high-temperature anti-oxidants, when used on bearing metals with low chemical reactivity as lead-free high-tin alloys.

Item C. Small difference in "L-value" (from 20 to 30%) is found between (1) Lead-containing and lead-free high-tin white metal; (2) Plain oil and the same oil containing normal amounts of high-temperature anti-oxidant.

In practice these differences are manifested in the following manner:

In bearings where the lubrication is predominantly fluid, e.g., steam engine bearings, etc., defects will only occasionally arise, even with the worst values for Item A.

In bearings where the service is so hard that casual contacts between the rubbing surfaces constantly may be expected, defects according to Item A will always be found, and often according to Item B, depending upon the severity of the service.

General Summary. A consideration of the results gives a series of conclusions of general character.

1. **Boundary Lubrication is a Primary Factor.** Boundary lubrication is a primary phenomenon which must be satisfied before hydrodynamic, fluid lubrication can be obtained. If fluid lubrication is obtainable without formation of a boundary lubrication film it would be indifferent which bearing metal and which oil were used. Experience shows the opposite, and results obtained by the tests show that the boundary lubrication film is formed most

Table I. Corresponding values of Brinell hardness, width of track and "L-value" for different alloys with 80% Sn.

Alloy Composition			Brinell Hardness 5/125/30	Width of Track, mm	"L-value" Percent
Sn	Sb	Cu			
80	10	10	32	0.68	51
80	16	4	29	0.57	29
80	20	0	25	0.68	57

Table II. Effect of aging on lead-containing and lead-free high-tin alloys.

Alloy Composition				Brinell Hardness 5/125/30		"L-value"	
				As Cast	Artif. Aged	As Cast	Artif. Aged
Sn	Sb	Cu	Pb				
83.5	8	6.5	2	30	29	19.5%	25%
84	9	7	0	30	29	21.5%	35%

quickly and strongly on the metal/oil combinations which, known from experience, are most satisfactory as bearing metals and lubricants. It is the rheological properties of these films which are responsible for the non-scoring properties in sliding.

2. The Boundary Film is Formed by a Chemical Process. The boundary lubrication film must be formed by a chemical reaction between bearing metal and lubricant, but no specific chemical or physical relation between metal and lubricants can be mentioned. However, semi-conductivity tests show enrichment of tin-oxide containing compounds in the track especially on the sides which consist mostly of matrix. If the surronding atmosphere is considered, it is most likely that chemical reactions take place in such a way that the metal acts as a catalyzer or oxygen-carrier for the oxidation of the oil to compounds which can adhere to (or combine with) the metal so as to form a film which prevents further metallic contact between the sliding metals.

These chemical reactions take place where the temperature and pressure are highest. This happens in the metallic contact points and especially in the lowest melting components of the structure. It is the chemical reactivity of the lowest melting structure components that is decisive. For the white metals it is, therefore, the matrix, which is specially able to react when it has been supersaturated after a quick solidification, or the eutectics present, particularly when they contain lead which is likely to promote film formation. As regarding the copper alloys, it is the presence of phosphorus in the lowest melting eutectics that influence film formation.

If high-temperature anti-oxidants are added, the oxidation mechanism is restricted and film formation is less pronounced. If a chemically inactive oil, such as silicone, is used, no boundary lubrication reaction can take place; consequently no boundary lubrication film can be formed and thus no fluid lubrication can take place in spite of the fact that silicone is a viscous fluid.

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COMMENTARY, by A. E. Roach (Research Laboratories Div., GMC). Dr. Lunn's paper deals with a subject of considerable practical importance to bearing and lubrication engineers. In commenting on it, I should like to review the probable course of events that may occur when a bearing and journal are operated under thin-film or boundary conditions.

Several investigators[1, 2, 3] have called attention to the importance of surface films, particularly oxides, in reducing friction and adhesion between surfaces in sliding contact. They point out that when metallic surfaces are chemically clean, they generally have large friction coefficients and tend to weld together readily. But when metallic surfaces are protected by layers of oxides and other contaminant films, they have smaller friction coefficients and resist welding together.

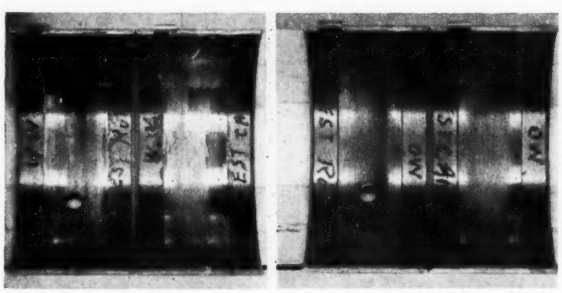

Fig. 1. (Left) Test bearing "A" after running 20 seconds with abrasive-containing oil charged with nitrogen; (Right) Test bearing "B" after running 5.5 minutes with abrasive-containing oil charged with compressed air.

When a bearing and journal touch each other in sliding contact, these protective films may be scrubbed and scoured away leaving what is for at least an instant bare clean metals. Conditions are then favorable for welding, scoring, and seizure.

As Dr. Lunn points out, lubricating oils may contain dissolved oxygen and other materials that have an affinity for clean metals. Consequently, the destructive process of scrubbing away surface oxides and other films may be accompanied by the

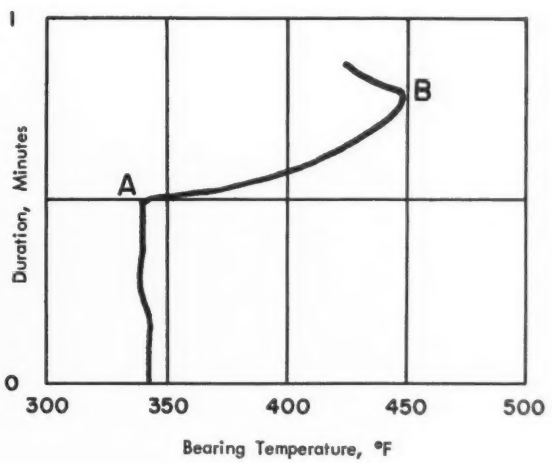

Fig. 2. Temperature-time record of test of bearing "A" run with abrasive-containing oil charged with nitrogen. Abrasive-containing oil admitted to bearing at point A. Bearing seized at point B. Duration of run 20 seconds.

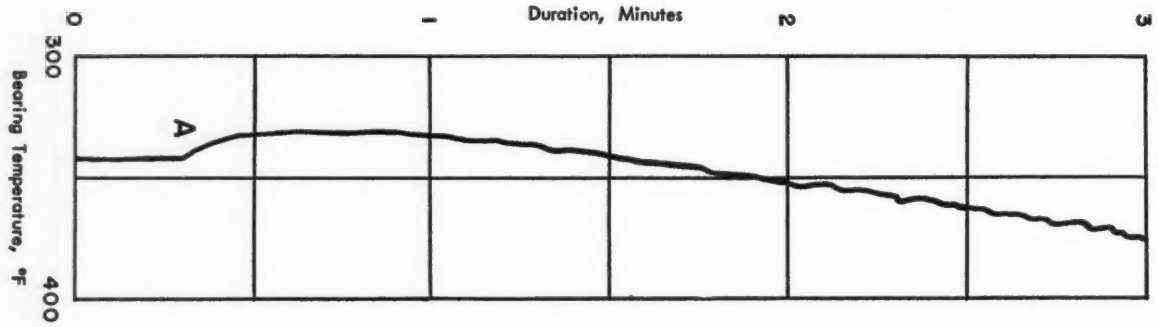

Fig. 3. Temperature-time record of test of bearing "B" run with abrasive-containing oil charged with compressed air. Abrasive-containing oil admitted to bearing at point A. Run terminated after 5.5 minutes because supply of abrasive-containing oil was exhausted. Bearing did not seize.

healing process of re-oxidizing and re-contaminating the surfaces. Whether a bearing will seize in a given situation may therefore depend upon the relative rates of these two processes, as well as upon the thickness and tenacity of the oxide layer after it has formed.

In his paper Dr. Lunn states that ". . . if the surrounding atmosphere is considered it is most likely that chemical reactions can take place in a way that the metal can act as a catalyzer or oxygen-carrier for the oxidation of the oil . . ." To this I would add that the oil must also act as an oxygen-carrier for the oxidation of the bearing metal.

Even a bearing metal as score-resistant as lead-base babbitt will readily score when oxygen-deficient lubricants are employed. Fig. 1 shows two bearings that have been run in an Underwood Centrifugal Bearing Test Machine[4] at 4000 rpm speed and 3000 psi unit load. The lubricant contained 1 gm of crystalline alumina (40 microns nominal size) per gallon to accelerate the scouring away of oxides and other surface films.[5]

In the case of bearing "A," the lubricant had compressed nitrogen bubbled through it for a few minutes before it was fed to the bearing; this bearing ran only 20 seconds after the lubricant was introduced to it (Fig. 2). Failure was by seizure (welding) to the journal. In the case of bearing "B," on the other hand, the lubricant had compressed air (21 per cent oxygen by volume) bubbled through it before it was fed to the bearing; the bearing ran 5.5 minutes and was then shut down only because the supply of abrasive-containing oil was exhausted (Fig. 3). This bearing did not fail.

These tests show that lubricants containing dissolved inert gases, such as nitrogen, tend to permit welding (seizing) of the bearing to the journal whenever their surfaces are exposed by abrasive action, while lubricants containing dissolved oxygen tend to prevent seizure of the bearing and journal by re-oxidizing the surfaces exposed by abrasive action. The tests further show that such re-oxidation occurs with great rapidity, even when the amount of oxygen in the oil is very small.

The effect of dissolved gases in the lubricant on the performance of oil-film bearings may be of interest in applications such as enclosed electrical machinery using inert gases as coolants, heat treating furnaces and drying ovens using inert atmospheres, and sealed refrigeration machines using oxygen-free refrigerants.

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AUTHOR'S CLOSURE. The discovery made by Mr. Roach is most interesting, and adds materially to our understanding of the problem of the sliding surface. It is pertinent to quote Prof. Finch to whom Roach referred (Ref. 1).

Prof. Finch says: "The problem of the sliding element is a very complex one. A distinguished physicist once spoke of it to me as 'a very messy business.' This complexity together with the success of the empirical approach has undoubtedly deterred scientific research into the subject."

Observations as Mr. Roach's are valuable for our understanding of the complexity.

2nd Annual ASLE-ASME Lubrication Conference

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(For list of papers to be presented see Page 227)

The Influence Of Moisture On The Friction & Surface Damage Of Clean Metals

by R. O. Daniels & A. C. West*

A new, controlled atmosphere, low-speed friction apparatus for fundamental boundary lubrication studies is described. The friction of a one-eighth inch diameter hemispherical slider on a flat disk is automatically plotted as a function of the desired operating variable on an "X-Y" type recording potentiometer. An investigation of the effects of moist surrounding atmosphere and bulk water on the kinetic friction of high purity, unlubricated metals is reported and a theory presented which explains the observed behavior in terms of an oxidizing reaction which occurs at the contacting asperities as they deform. The oxidation is accelerated at the freshly exposed metal surfaces by the presence of adsorbed moisture and by any rise in temperatur which may occur, with the result that friction and surface damage are reduced.

The influence of moisture in lubrication phenomena has been recognized previously in the published literature. Rayleigh[1] showed that the coefficient of static friction between lubricated surfaces under boundary conditions increases when water is added to the lubricant. Hardy[2] and his collaborators found that water could either increase or decrease the friction, depending upon the material of the sliding surfaces and the nature of the lubricant film. Rhodes and Allen,[3] as well as Campbell,[4, 5] found that water vapor in the air caused a rise in static friction. Tingle[6] studied surfaces lubricated with a fatty acid and found moisture to be essential to chemical reaction leading to the formation of a metal soap, which results in a low coefficient of friction.

The present investigation of the effect of moisture on friction and wear employs kinetic friction measurements on clean metal surfaces. A better understanding of the phenomena which occur at the contacting surface asperities during unlubricated sliding will aid in further understanding the basic principles of lubricated surface interactions.

EXPERIMENTAL APPARATUS & TECHNIQUES. Friction Apparatus. The apparatus used was a new, low-speed friction apparatus designed to study boundary lubrication under controlled conditions. The specimen geometry is similar to that used in the Bowden-Leben[7] apparatus and provides for the measurement and recording of the coefficient of friction between a one-eighth inch diameter, hemispherical slider and a flat disk. The apparatus is operated in a chamber within which a clean, dry atmosphere is continuously maintained. In addition to determining the mean value of the friction coefficient, the "stick-slip" phenomenon can be observed.

The details of the apparatus are shown in Fig. 1. A one-inch diameter, flat disk is mounted in a suitable holder which is clamped on a small heating plate. This heater is located in a carriage bolted to one end of a pair of laterally flexible steel support blades, the other ends of which are firmly secured to a chromium plated steel surface plate. Transverse motion is given the carriage by the expansion of an oil filled drive bellows. The slider is mounted in a holder at the end of an arm which is pivoted with two degrees of freedom. Weights placed at the end of this arm apply the load between the two test specimens. As the bellows moves the specimen disk, the slider resting upon it bears against the actuat-

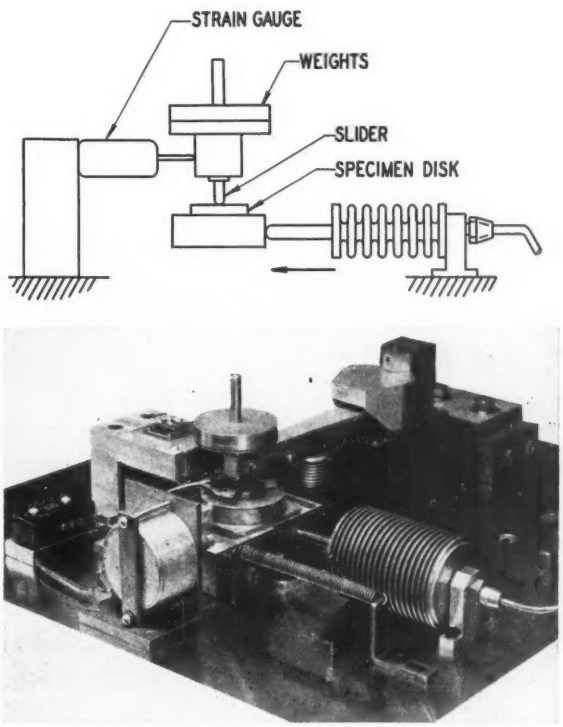

Fig. 1. Low-speed friction apparatus detail.

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(This paper was sponsored by the ASLE Technical Committee on Lubrication Fundamentals, and presented at the ASLE 10th Annual Meeting, Chicago, April 14, 1955.)

ing element of a strain gauge; and its output is fed through a control unit to an "X-Y" type recording potentiometer, which plots the coefficient of friction as a function of the desired operating variable, e.g., time, temperature, etc.

Other details of the apparatus are an auxiliary bellows for raising and lowering the slider carrying arm, a thermocouple, a limit switch which indicates when the carriage has reached the extremity of safe travel, and a motor used to slide the specimen holder laterally in the carriage. A glass dome, gasketed to form a tight seal with the base plate, may be placed over the entire apparatus and the friction measured in vacuum, inert gases, or in specially prepared and controlled atmospheres.

Fig. 2 is a general view of the apparatus and associated equipment. The apparatus is shock-mounted to minimize vibration and is housed within a controlled atmosphere chamber. Work may be carried on within the chamber through the rubber-gloved ports located in the Lucite face. The operation of the apparatus, however, is entirely controlled from outside the chamber. The sliding velocity of the test specimens is controlled by adjusting the rate of flow of oil into the main drive bellows of the apparatus. The apparatus may be operated at sliding velocities ranging from 0.00005 to 0.1 cm./sec. at loads from 30 to 500 grams on the slider and temperatures from 70 F. to 850 F.

Air Purification System. The air purification system is described in detail because one of the important features of this apparatus is the control of the atmosphere surrounding the test specimens. A slight, positive pressure of clean, dry air from the scrubbing system is maintained in the chamber 24 hours a day. The air scrubbing system consists of a series of five, three-inch diameter glass columns, each four feet long. The first is filled with soda lime which absorbs carbon dioxide, sulfur dioxide, and other acid gases. The second and third columns are filled with Drierite to adsorb moisture, and the fourth column contains fluidized, highly absorptive, 200-mesh silica gel which removes any remaining traces of polar components. The last column is filled with loosely packed glass wool which filters out entrained particles. The air finally passes through a pressure regulating valve which maintains the air at a positive pressure of one to two millimeters of mercury within the test chamber. The air within the chamber is recirculated by a blower through an auxiliary drying unit filled with Drierite. This purification system maintains the relative humidity of the air at less than 0.25% and cleaned specimens can be stored within the chamber for several weeks without contamination. With the glass dome in place, the apparatus can be operated in vacuum or any desired atmosphere.

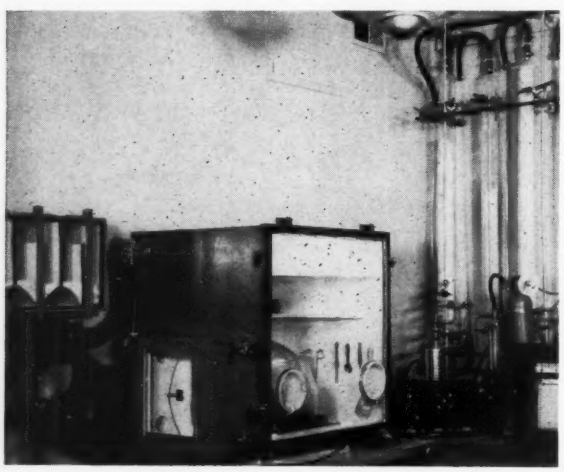

Fig. 2. General view of the low-speed friction apparatus and associated equipment.

Specimen Preparation. Friction measurements are significantly affected by the surfacing and cleaning techniques employed in preparing the test specimens. The following method of specimen preparation gives reproducible results:

1. The disk specimens are rinsed in fresh, boiling ethylene dichloride and abraded, dry, on No. 400-A Durite polishing paper using a special holder to avoid contamination by handling. This procedure is repeated three times.
2. The disks are polished in random directions on No. 600-A Durite paper under flowing distilled water.
3. The disk surface is then scrubbed with levigated alumina to remove loose metal fragments and abrasive grit, rinsed under distilled water, scrubbed with a degreased Selvyt polishing cloth while held submerged in methyl alcohol. The specimen is then transferred to an ethylene dichloride vapor degreaser where it is left for 15 minutes.
4. Upon removal from the degreaser, the disk is suspended in a clean glass vessel, which is immediately evacuated. High purity nitrogen, at approximately 1 mm. pressure, is allowed to flow through this vessel as it is heated to 400 F. and held there for 15 minutes. The nitrogen flow is then terminated. The vessel is evacuated, allowed to cool, sealed and transferred into the clean air chamber of the friction apparatus where the specimen is removed and stored ready for use.

An abbreviated cleaning procedure is satisfactory for the sliders. The freshly machined slider is rinsed two or three times in fresh portions of boiling ethylene dichloride and transferred into the clean atmosphere chamber.

Procedure. The procedure for obtaining the experimental data herein reported was as follows: In each experiment, the slider was of the same metal as the disk, and the observations were all made at room temperature. The coefficient of friction of specimens was first measured in clean, dry air, using a load of 200 grams and a sliding velocity of 0.04 cm./sec. Each observation consisted of a single traverse by the slider across a fresh portion of the disk. At least three observations were made in clean, dry air to establish the coefficient of friction under this reference condition. The relative humidity within the lowered dome of the friction apparatus was then increased by passing a portion of

the incoming air through a heated flask containing distilled water.

The air within this dome was continuously circulated, withdrawn near the surface of the friction specimens, and ejected through a diaphragm-type hygrometer. The relative humidity reported was the reading on the hygrometer as the air was withdrawn. Over a period of about 30 minutes, the relative humidity was slowly raised to between 90% and 100%, and the friction measured intermittently. After maintaining this humidity for five to ten minutes, the moisture in the air stream was cut off, and clean, dry air was again passed through the apparatus until the humidity returned to its original low value. At least two observations of the coefficient of friction were again made. The surface was then flooded with distilled water, and several observations of the friction were made. Finally, the excess water was removed and the surface dried by the passage of clean, dry air for several minutes. The friction was again measured in this dry condition.

Throughout this investigation, the surface damage, which occurred during the friction measurement, was observed by microscopic examination of the wear track. All of the disks were photographed at a magnification of 10X and selected areas at magnifications ranging from 100X to 500X.

RESULTS. A study was made of the influence of moisture on the frictional behavior of aluminum, iron, SAE 1020 steel, tin, chromium, nickel, copper, and silver. All of the metals except the steel were of at least 99.95% purity. The results of these investigations are shown in Fig. 3. The unlubricated friction values in clean, dry air (reference condition) were in the range from 1.0 to 1.6 for all of the high purity metals; for SAE 1020 steel, the friction was somewhat lower, about 0.8.

The observations in a clean, moist atmosphere showed that, for a majority of the metals tested, the coefficient of friction was lower than in the dry air reference condition. On a few metals, there was only a slight effect. The lowering of the friction by moisture in the surrounding atmosphere was frequently found to occur when only a slight amount of moisture was present.

When flooded with distilled water, aluminum, iron, SAE 1020 steel, tin, and chromium gave coefficients of friction approximately the same as observed in a moist atmosphere. For copper, however, and most strikingly for nickel, flooding the surface with water increased the friction coefficient to approximately that observed in dry air. For silver, neither water vapor in the surrounding atmosphere nor bulk water on the surface caused significant change in the coefficient of friction. These behaviors in the presence of water are explained by the mechanism presented under "Discussion."

The reversible nature of the influence of moisture bears emphasis. In each interval during the course of a test series when the friction was measured in a clean, dry atmosphere, a high value was consistently obtained regardless of whether the observation was made immediately after cleaning the specimen, after subjecting it to a moist surrounding atmosphere and drying, or after flooding it with distilled water and drying. The reversible nature of this effect indicates that surface chemical reaction over the entire surface is not responsible for the lowering of friction in the presence of moisture. Bowden and Tabor[8] showed that the first molecular layer of moisture adsorbed on a clean, degassed metal surface is chemically bound but that adsorption thereafter is physical. Inasmuch as the cleaning procedure used for our work did not include degassing the surface or other removal of this initial layer of water, the observed, reversible, physical adsorption is to be expected.

DISCUSSION. It is commonly accepted that the friction and surface damage between sliding metals is largely determined by the films grossly covering the surface. Analysis of the foregoing data suggests that the instantaneous reactions which occur within the actual area of contact as sliding proceeds are also significant. These chemical reactions at the tips of sliding asperities are generally recognized as important in the action of extreme pressure lubricants, but their significance in the unlubricated sliding of clean metals has not been properly appreciated. The following theory emphasizes the importance of the chemical reactions which occur within the area of sliding contact, explains the influence of moisture, and is in harmony with other published data.

It is postulated that the coefficient of friction is significantly influenced by an oxidizing reaction at the fresh metal surfaces exposed during the deformation of contacting asperities. It is proposed that this oxidation is accelerated and the friction subsequently lowered, by the presence of adsorbed water and any temperature rise which may exist, due either to frictional heating or to the exothermic oxidation reaction itself. This accelerated reaction at the deforming asperities is believed to replace metal-to-metal junctions by oxide or hydrate junctions; and the resulting coefficient of friction is then

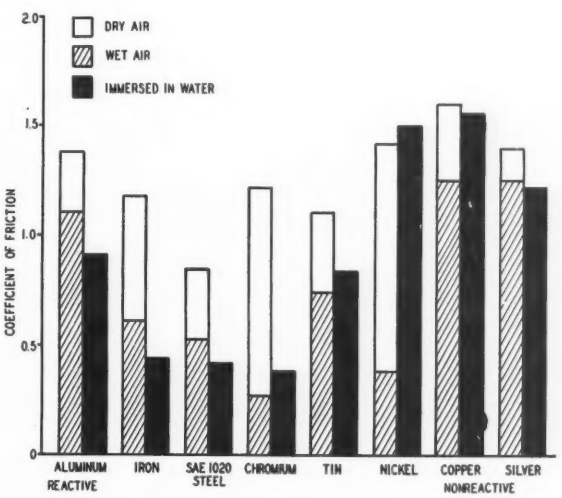

Fig. 3. Kinetic friction of unlubricated metals in dry air, moist air, and immersed in water.

determined by the rate of the reaction and the physical nature of the oxidation products formed.

According to the proposed theory, moisture causes a decrease in friction when the following two conditions are fulfilled. First, the oxidizing reaction within the area of sliding contact must proceed at a rate sufficiently rapid to reduce materially the amount of metal-to-metal contact. Second, the oxidation products, together with the underlying metal, must form a low friction combination.

For aluminum, the oxide reaction occurs rapidly, but the brittle aluminum oxide does not provide a low friction coating on the soft underlying metal; therefore, moisture causes only a small reduction in the coefficient of friction, as shown in Fig. 3. For tin, the observed decrease in friction due to moisture is again relatively small because a similar brittle oxide is formed; and, in addition, the oxidation reaction rate is slower than with aluminum. On iron and steel, moisture reduces the coefficient of friction to approximately one half of its value in the clean dry air reference condition because the oxidation products prevent more effectively the formation of metal-to-metal junctions as sliding proceeds. In the case of chromium, the oxide film undergoes elastic deformation and is remarkably resistant to penetration, as shown by Wilson.[9] Thus, the accelerating influence of moisture on the oxidation reaction results in a large reduction in friction.

The proposed mechanism also satisfactorily explains the behavior when the surface is flooded with water. The limited amount of oxygen absorbed in bulk water, together with its relatively low mobility, greatly reduces the oxygen available for chemical reaction at the metal surface. Approximate calculations indicate that the oxygen available to the surface asperities corresponds to a concentration in air of 5×10^{-5} per cent oxygen. Only on the more reactive metals does this oxygen scarcity permit appreciable oxidation at the tips of deforming asperities in spite of the accelerating influence of the surrounding water. Thus, the coefficient of friction when the surface is flooded with water is approximately the same as when in moist air for aluminum, iron, steel, chromium, and tin. On nickel the formation of a protective oxide in the area of contact proceeds at a sufficiently rapid rate to give a low friction value in moist air; however, with the surface flooded with water, the low oxygen availability, together with the low reactivity of nickel, reduces the rate of formation of the protective oxide, and the friction is about the same as in dry air. On copper, which is also relatively nonreactive, a similar behavior is observed. In the case of silver, the metal is sufficiently nonreactive so that there is no appreciable formation of oxide within the area of sliding contact even in moist air, and the friction remains high.

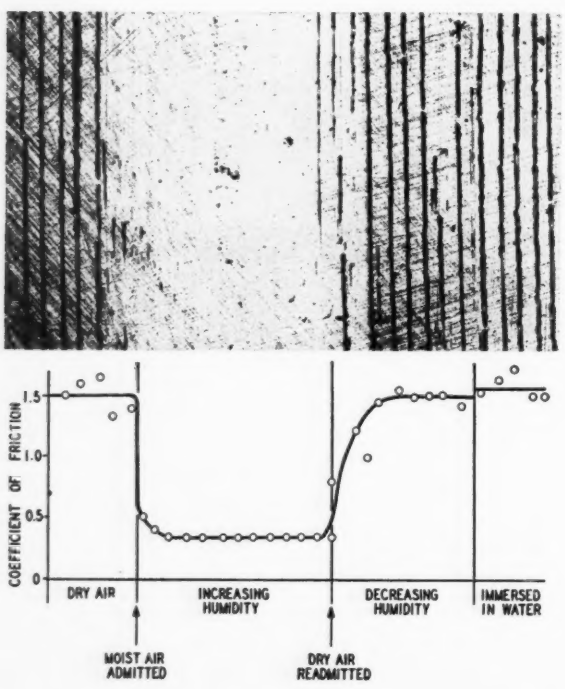

Fig. 4. Photomicrograph of surface damage correlated with the observed coefficient of friction (Ni on Ni).

The friction and wear reducing ability of an oxidation reaction, as proposed in this paper, has also been observed on lubricated surfaces by Murray and Johnson.[10] They suggest that the poor lubricating ability of silicone oils on ferrous surfaces may be due to their ability to prevent normally available oxygen from reacting with the surfaces to form oxides. They report that peroxide additives in silicones cause a significant improvement in their effectiveness as boundary lubricants. Although the present investigation does not include a systematic study of the effect of oxidizing agents in bulk water, the friction of nickel, copper, and silver was measured in the presence of hydrogen peroxide. Although it is not proposed that hydrogen peroxide functions in the same manner as adsorbed oxygen and moisture, in every case the friction was markedly lower than for the water flooded surface. This adds support to the proposed concept that oxygen scarcity is responsible for the observed high friction of relatively nonreactive metals when flooded with water.

Microscopic examination of the test specimens offers additional proof that the lowering of friction in the presence of moisture is due to a reduction in the amount of metal-to-metal welding which occurs for the surface damage was found to correlate with the coefficient of friction. Photomicrographs showed that sliding in a clean, dry atmosphere caused a large amount of surface deformation and erratic seizure. On some of the soft metals there was evidence of accumulative metal transfer to the slider until a rather large weld occurred. When this junction finally sheared, a large agglomeration of metal remained firmly attached to the disk. Immediately following such a seizure, the surface of the disk was frequently undisturbed, indicating that the slider "jumped ahead" scarcely touching the surface.

In a moist atmosphere, the metals which exhibited a decrease in friction showed a large reduc-

tion in surface damage. The wear tracks across the surface of a nickel disk, as shown in Fig. 4, suddenly changed from the severe surface damage and intermittent seizure, characteristic of sliding in clean, dry air, to a barely detectable mark as a moist atmosphere was introduced. The coefficient of friction values which prevailed during each traverse are plotted immediately below the wear tracks; the correlation between friction and surface damage is clearly shown.

The temperature rise which occurs at the tips of contacting asperities is often of interest in friction and wear studies. An equation[11a] for the temperature rise in the area of contact due to frictional heating, though of questionable accuracy at very low sliding velocities, indicates that under the conditions of the present experiments the temperature rise should be negligible. However, in studying the present data, a correlation was noted between the influence of moisture on the frictional behavior and the heat of formation of the various metal oxides. [In Fig. 3, the metals are arranged in the order of decreasing heat of formation of the metal oxides from 389 kilocalories/mol for aluminum oxide (Al_2O_3) down to 6.9 kilocalories/mol for silver oxide (Ag_2O).]

This general correlation leads to the interesting speculation that on a microscopic scale the tips of sliding asperities may be heated by the exothermic oxidation reaction. If this heat, together with any frictional heating which may occur, could cause a temperature rise of even 10 C., the rate of the oxidizing reaction at the freshly exposed metal surface would approximately double. This increase in reaction rate would lead to further heating, and the process would be accumulative. The heat might well be concentrated in the oxide layer because its thermal conductivity is lower than that of the metal. Any significant thermal gradients in the load-bearing junctions could create high stresses at the metal-oxide interfaces, which would aid in shearing the junctions and thus lower the friction.

The occurrence of extremely "hot spots" caused by the liberation of heat from such an oxidizing reaction has recently been discussed by Bowden.[12] His observations were at higher loads and much higher sliding velocities than those of the present studies, and there is no question that the amount of heat is much greater under such conditions. Nonetheless, the same principles apply in both cases; the peak temperatures attained under the two conditions are merely matters of degree. Although very high temperatures are certainly not present under the low-speed conditions used in the present studies, the effect of a temperature rise of but a few degrees should not be overlooked.

In the present investigation, a friction value of 1.2 was observed for unlubricated chromium-on-chromium in dry air. This is believed to be of particular interest because the coefficient of friction commonly reported is 0.3 to 0.4. When the customary load of 200 grams was used, the coefficient of friction varied erratically from 0.3 to 1.2. Increasing the load to 400 grams eliminated this variation and produced a well defined value in clean, dry air of 1.2 and a stable coefficient of 0.3 in moist air. The unusual amount of protection afforded by the normal chromium oxide surface film has been pointed out by Wilson,[9] who reported a coefficient of friction of 0.3 using a similar specimen geometry at loads up to 100 grams. Bowden, Gregory, and Tabor,[11b] working with a 4000-gram load, reported the friction of chromium to be 0.4. These values, however, were both obtained in atmospheres which certainly contained water vapor. In the present studies, the friction obtained in a moist atmosphere is in agreement with these previously reported values; however, the friction coefficient of 1.2 obtained in a dry atmosphere appears to be more consistent with the behavior of other clean metals.

Whitehead[13] reported similar behavior for copper. At very light loads he found shearing took place within the oxide film, and the friction was relatively low. As the load was increased to 10 grams, the friction coefficient rose abruptly to 1.6. The principal difference between the behaviors of these two metals is that the copper oxide film is less effective in preventing metal-to-metal contact than the chromium oxide film. The transition from oxide sliding on oxide to significant metal-to-metal contact occurs at loads of only a few grams on copper rather than the much higher load and dry atmosphere required with chromium.

SUMMARY. A new, low-speed friction apparatus for fundamental friction and boundary lubrication studies in the speed range from 0.00005 to 0.1 cm./sec. is described. This apparatus, located in a closed chamber within which a controlled atmosphere is maintained, measures the force required to move a one-eighth inch diameter slider across a flat disk and automatically plots the coefficient of friction as a function of the desired operating variable on an "X-Y" type recording potentiometer.

An investigation of the effect of adsorbed moisture and bulk water on unlubricated kinetic friction and wear is reported. It is concluded that even in the unlubricated sliding of clean metals, surface chemical reactions which take place in the areas of sliding contact have a significant effect on friction and surface damage. A theory is proposed which explains the influence of moisture in terms of (1) an oxidizing reaction which occurs at the contacting asperities as they deform and (2) the nature of the oxidation products formed. The oxidation is accelerated at the freshly exposed metal surfaces by the presence of adsorbed moisture and by any rise in temperature which may occur. The friction and surface damage are thus reduced because many of the metal-to-metal contacts are replaced by oxide or hydrate junctions which shear more easily than the metal welds.

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COMMENTARY, by Dr. E. Rabinowicz (Massachusetts Institute of Technology). The meticulous care taken by the authors in the cleaning of their specimens and the control of their atmosphere has produced results that have increased markedly our knowledge of the effect of moisture on the friction of unlubricated metals. I wonder whether the authors adopted their cleaning procedure by a trial-and-error method or by a study of techniques recommended in the literature. My reason for raising this point is that washing a specimen with organic liquid may deposit a trace of impurity from the liquid onto the surface as easily as remove the last trace of contamination from the surface. Vapor degreasers are more satisfactory, but the high vapor pressure of some impurities might give difficulties even there. In any case, I am happy to note the satisfactory agreement of the authors' friction values with those obtained on specimens abraded dry but otherwise untreated.

The fact that moisture has such a profound effect on friction makes it difficult to justify the carrying out of sliding tests on unlubricated surfaces in air whose moisture content is unknown. Do the authors think that similar differences in friction are observed with well-lubricated surfaces?

The conclusion that the presence of water in bulk form decreases the availability of oxygen and thus may slow down chemical reaction is of great interest and importance. I myself have observed an analogous effect with titanium. In this case, a change of friction with viscosity appears due to the fact that the high viscosity oils decrease the rate at which oxygen can get to the metal surface. Although other complicating effects may make interpretation of the results difficult, it is possible that the same behavior can be produced in the authors' experiments by the use of moist air below O°C., which will form a solid, adsorbed moisture film relatively impervious to the atmospheric oxygen. Are the authors planning to carry out any tests at low temperature?

AUTHORS' CLOSURE. In adopting the cleaning procedure, we investigated some of the techniques described in the literature and also experimented with various alternate procedures of our own. We found that specimens cleaned with an organic solvent evidenced traces of impurities on the surface until a heating step was added to the cleaning procedure. After heating to 400 F. in high purity nitrogen at approximately 1 mm pressure, reproducibly clean surfaces were obtained.

Dr. Rabinowicz raises a most pertinent question in regard to the effect of moisture on the friction of lubricated surfaces. It has already been pointed out in the literature that moisture is required in order to achieve effective lubrication by a fatty acid. A more detailed study of the role of moisture in lubricated friction is currently in progress and perhaps can be reported at some future date.

Moist air below 0°C., which would form a solid adsorbed moisture film on a metal surface, would indeed be an interesting barrier to exclude atmospheric oxygen. However, it is our opinion that the resulting friction would be more closely related to the friction of ice than to the exclusion of oxygen from the surface. No low temperature studies are contemplated.

Current Literature

'Wedge-Lock' Mechanical Seals. Bulletin CP551 describes the new Chempro mechanical seals that can be installed in 20-30 minutes, requiring no special holding clamps or machining of stuffing-box faces. Completely interchangeable with stuffing-box packing, the seals give highly successful and economical service on pumps handling acids, caustics, solvents, and other liquids and slurries under a wide range of operating conditions. They have been successfully used under slurry conditions that previously could not be sealed by a mechanical seals. (Chemical & Power Products, Inc., LE-11/4, 11 Broadway, New York City 4.)

Sintered Bronze Filters. How "a handful of bronze balls started a new industry" is explained in a recently published 16-page catalog of sintered bronze filters. Made of fusing together millions of microscopic bronze balls, this relatively new filter medium never has to be replaced (it is cleanable, re-usable) and is virtually unaffected by temperature extremes and corrosive liquids and gases. The catalog includes basic information on porous bronze as a filtering medium for natural gas, chemicals and petroleum products used in municipal, county, and other installations. A final section explains how the company, which pioneered the use of porous bronze filters, now offers its

(Continued on Page 279)

Effect Of Air & Nitrogen Atmospheres On The Temperature Limitations Of Liquid & Solid Lubricants In Ball Bearings

by Z. N. Nemeth & W. J. Anderson*

Tests of 20 mm bore tool steel ball bearings operated at 2500 rpm are reported. All lubricants tested in both nitrogen and air atmospheres were effective to higher temperatures in a nitrogen atmosphere. Comparison of all lubricants showed that solid lubricants (molybdenum disulfide and graphite) were best in either air or nitrogen atmospheres. Both graphite in air and molybdenum disulfide in nitrogen were effective to 1000 F. Although a silicone diester oil was effective to 1000 F., in nitrogen atmosphere, heavy carbonaceous deposits prevented the bearings from rotating freely after cooling to room temperature.

The problem of providing lubrication for aircraft turbojet engine bearings is becoming more severe because of the steady increase in engine operating temperatures.[1-4] Lubricants are limiting bearing operating temperatures because they are temperature limited by evaporation, thermal decomposition, and oxidation characteristics.[1, 5, 6] Low bearing temperatures require high lubricant flows and ultimately result in a burden on the available means of removing this heat from the lubricant. Other than the use of refrigeration systems, with resulting weight and complexity, the only available means to cool the lubricant are ram air and fuel. Increased flight speeds will reduce the cooling effectiveness of both of these fluids because of increased ram air temperatures and possible increases in bulk fuel temperatures due to skin heating. A reduction in the oil system heat load, which could be accomplished by letting the bearings operate at higher temperatures, would alleviate this acute cooling problem. This cannot be done, however, until lubricants with better high temperature stability are developed. Solid lubricants[7-9] have shown some promise as high temperature lubricants and inert atmospheres may be effective in extending the temperature limits of liquid lubricants. Exclusion of oxygen from liquid lubricants has been shown to effectively reduce neutralization number (Ref. 9, discussion by McLain). The use of closed lubrication systems may make it feasible to control the atmosphere surrounding the lubricant.[10]

The work reported herein is a continuation of that reported in Refs. 8 and 9. The research includes a comparison of the temperature limitations of a petroleum, a synthetic liquid, and a solid lubricant (molybdenum disulfide) in air and in nitrogen atmosphere. Results for graphite in air and for dry runs with nitrogen are also reported. Tool steel ball bearings of 20 mm bore were run at 2500 rpm under 110 pounds thrust load at increasing temperatures until the bearing had either failed or had run for two hours at 1000 F.

This investigation was conducted at the NACA Lewis laboratory, Cleveland, Ohio.

TEST EQUIPMENT. The bearing rig (Fig. 1) was constructed around a floor type drill press and is described in detail in Ref. 8. The test bearing housing was supported on an externally pressurized thrust bearing; the housing was restrained from moving circumferentially by a strain gage assembly which measured friction force. A resistance furnace surrounded the test bearing housing. Load was applied by means of a lever and dead weight system which applied load in the axial direction. Temperatures were obtained by thermocouples in the housing and on the shaft.

Test bearings were size 204, 18-4-1 tool steel ball bearings. All but one of the test bearings were equipped with two piece stamped and riveted silver plated copper beryllium cages. One bearing was equipped with a two piece machined and riveted cast Inconel cage.

The petroleum lubricant used was MIL-0-6081A grade 1010 oil. It had a viscosity 40,000 centi-

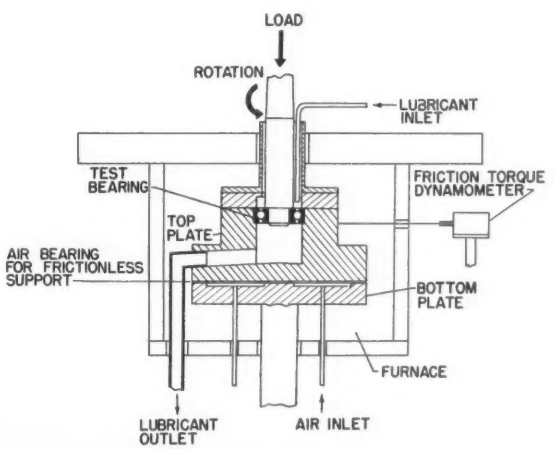

Fig. 1. Schematic diagram of bearing test rig.

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(This paper was sponsored by the ASLE Technical Committee on Bearings & Bearing Lubrication, and presented at the ASLE 10th Annual Meeting, Chicago, April 14, 1955.)

stokes at —65 F., and 2.47 centistokes at 210 F. The synthetic lubricant used was a silicone-diester blend consisting of 1/3 di(2-ethylhexyl)sebacate, 2/3 methylphenyl polysiloxane (100 centistokes at 77 F.) and 0.5 percent phenothiazine. The blend had a viscosity of 3750 centistokes at —65 F., and 14.2 centistokes at 210 F. Solid lubricants used were molybdenum disulfide and graphite, both of which had an average particle size of 25 microns. The maximum size was 100 microns for both. In several tests, bearings were run in atmospheres of either oil-pumped nitrogen or prepurified-nitrogen.

Liquid lubricants were introduced in droplet form and solid lubricants in the form of an air mist. The flow rate of liquid lubricants was 0.0002 to 0.001 pound per minute and that of solid lubricants 0.00002 to 0.00015 pound per minute. Full details of the lubricant supply system are given in Ref. 8.

In no test was a bearing run continuously for more than 8 hours (the length of a work shift). Therefore all tests, other than those in which bearings failed in a short time (those run without lubricant), were shut down and restarted at least once.

PROCEDURE. Most runs were conducted at a constant speed of 2500 rpm and 110 pounds thrust load over a range of bearing temperatures from 100 F. to 1000 F., or failure, whichever occurred first. Test bearing temperatures were raised in increments of 150 F., and test bearings were operated continuously during the time required (about 1 to 1¼ hours) to reach each temperature level and for 2 hours after the designated temperature had been reached. A test was ended when either a lubrication or a bearing failure occurred or when 2 hours successful operation at 1000 F. was obtained. Failure was characterized by combination of high (in excess of 0.5 inch pound) and unstable friction torque and noisy test bearing operation. While torque value of 0.5 inch pound for failure indication is arbitrary, it is based on experience in this test rig. Failure occurred, generally, when 0.5 inch pound torque was exceeded. Failure due to cage breakage could be detected by visual inspection during shut down if other means failed to indicate trouble. Three special tests were conducted at 1000 F. In one, a bearing lubricated by MoS_2 was run for 2 hours in a nitrogen atmosphere. In another, a bearing lubricated by graphite was run for 20 hours in an air atmosphere. In a third, a bearing was run with graphite lubrication; during this test the lubricant supply was cut off to determine the length of time between lubricant cutoff and failure.

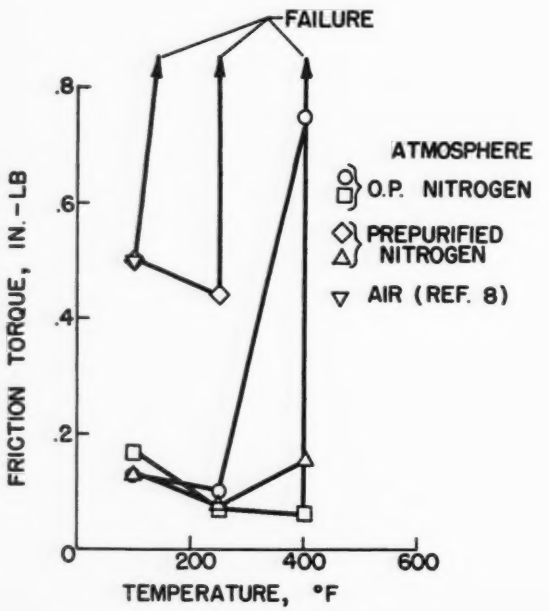

Fig. 2. Effect of temperature on friction torque of test bearings run dry in air and nitrogen.

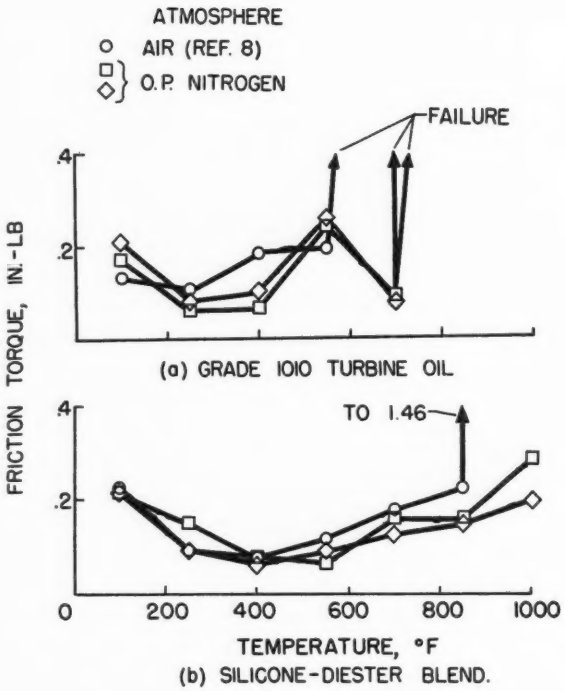

Fig. 3. Effect of temperature on friction torque of test bearings when lubricated with liquid lubricants in oil-pumped nitrogen and in air atmospheres.

The desired atmosphere was maintained around the test bearing by introducing the gas through the lubricant inlet tube (see Fig. 1). Excess gas escaped up through the chimney surrounding the test bearing shaft and down through the lubricant outlet tubes. Nitrogen gas was introduced not only during the test, but also during the preheat period prior to running and during the cooling period after the test.

RESULTS & DISCUSSION. The results of this investigation, which consisted of nineteen tests, are summarized in Table I and in Figs. 2 to 6 .

Inert Atmospheres. Four tests were run dry to determine the effect of an inert atmosphere on the length of running time to failure. Two tests were run with oil-pumped nitrogen and two tests with prepurified nitrogen. The results of these four tests, together with a dry run in air (data from Ref. 8) from comparative purposes are shown on Fig. 2.

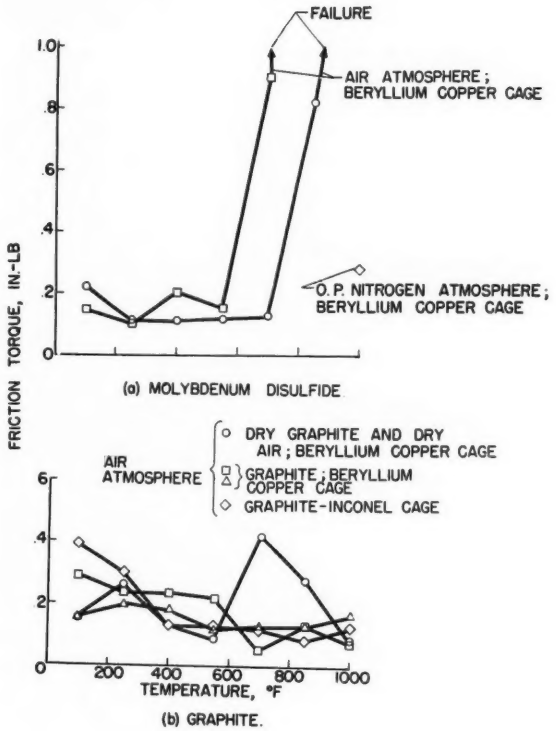

Fig. 4. Effect of temperature on friction torque of test bearings when lubricated with solid lubricants (majority of data from Ref. 8).

In both of the runs with oil-pumped nitrogen (tests 8 and 9) the bearings ran approximately 8½ hours before failure. Failures occurred in the 400 to 550 F. temperature range. In the two runs with prepurified nitrogen (tests 16 and 17) failures occurred after 4 and 7½ hours at temperatures of 250 and 400 F. In all four nitrogen runs the bearings survived longer than in air where failure occurred after slightly more than 3 hours. In all of these dry runs failures were characterized by cage fractures (Figs. 6a and 6b.)

These results indicate that in the absence of a lubricant, an inert atmosphere is more beneficial for bearing operation than is an oxidizing atmosphere. The slightly better results with oil-pumped nitrogen over prepurified nitrogen indicate that the minute quantities of oil present in the oil-pumped nitrogen may have provided some lubrication.

Liquid Lubricants. The effect of an inert atmosphere on the temperature limitations of liquid lubricants was determined using 1010 petroleum oil and a silicone-diester blend in air and oil-pumped nitrogen atmospheres. The results for 1010 oil are shown in Fig. 3a and those for the silicone-diester blend in Fig. 3b. In an air atmosphere (test 12, data from Ref. 8) 1010 oil was effective to 550 F., and in a nitrogen atmosphere (tests 10 and 11) it was effective to 700 F. In tests 10 and 12 the bearings sustained cage fractures (Fig. 6c) but no mechanical failure occurred in test 11. Fig. 3b shows the results for the silicone-diester blend. In an air atmosphere the silicone-diester blend was effective to 850 F. (test 15, data from Ref. 8). At this temperature friction torque reached a maximum of 1.46 inch-pounds but the bearing did not fail. In a nitrogen atmosphere (tests 13 and 14) the silicone-diester blend lubricated effectively at 1000 F. All three bearings showed heavy carbonaceous deposits (Fig. 6d). After cooling to room temperature the bearings run in tests 13 and 14 became inoperative because of hardened deposits. An inert atmosphere permitted bearing operation at higher temperatures with both liquid lubricants. Decrease in the availability of oxygen reduced the amount of lubricant oxidation.

Solid Lubricants. Three tests were run using MoS_2, two in an air atmosphere and one in a nitrogen atmosphere; results are shown in Fig. 4a. Using an air atmosphere the bearing of test 5 (data from Ref. 8) survived a complete test including the two hour run at 1000 F., but the cage was severely corroded (Fig. 6e). In another air atmosphere test (test 6) the bearing failed 30 minutes after the 2 hour run at 700 F. The cage was broken but not as badly corroded as in test 5. In test 7 a bearing was run for 2 hours only at 1000 F. in a nitrogen atmosphere. The bearing ran smoothly with low friction torque. After the test it was free and no evidences of corrosion were present (Fig. 6f).

At temperatures above 700 F. in the presence of oxygen, MoS_2 will oxidize to form abrasive and corrosive products. The severe corrosion present on the cage of bearing 31 after test 5 (Fig. 6e) and the clean appearance of bearing 58 after test 7 (Fig. 6f) are clear evidence of the damage caused by the oxidation products of MoS_2.

Four tests were conducted using graphite as a lubricant in an air atmosphere (all tests 1, 2, 3, and 4 are from Ref. 8). The results of these tests are shown in Fig. 4b. Tests 1 and 4 were run using bearings with silver-plated beryllium copper cages.

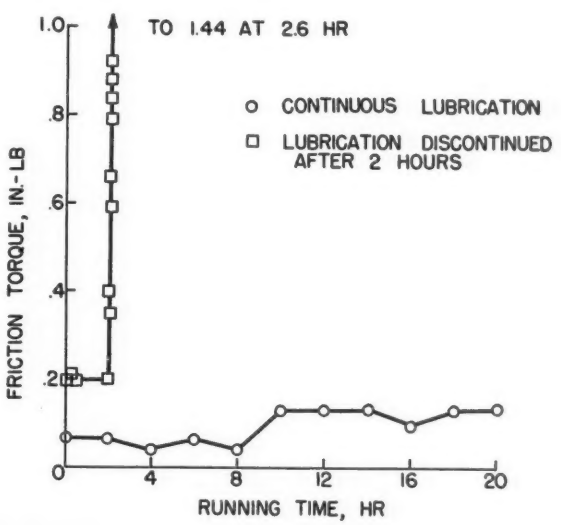

Fig. 5. Effect of running time on friction torque of test bearings when lubricated with graphite-air mist at 1000 F.

Both bearings completed 2 hours at 1000 F., and were clean and free after the test (Fig. 6g). Test 2 was run with graphite that had been baked for several hours to remove moisture. Specially dried air with a dewpoint below —68 F. was used. Despite these efforts to remove moisture from the graphite and air it was still an effective lubricant. The bearing completed 2 hours at 1000 F., and was in good condition after the test. In test 3 a bearing with a cast Inconel cage was used. As in the other three tests this bearing ran with low friction torque and was in good condition after the test. Under the conditions of these tests graphite was the best high temperature lubricant. Since graphite was an effective lubricant in an air atmosphere, it was not tried in a nitrogen atmosphere.

To further check the effectiveness of graphite as a high temperature lubricant, and also to check the effect of interruption of lubricant flow at 1000 F., two additional tests were run. In test 18 a bearing was run for 20 hours at 1000 F. The bearing ran with low friction throughout the test and after the test it was clean, free and otherwise in good condition. In test 19 the importance of the presence of the lubricant was determined by running a bearing at 1000 F., and then cutting off the supply of graphite. A plot of friction torque against time is shown in Fig. 5. After the flow of graphite was stopped, friction torque began to rise almost immediately. The bearing was allowed to run for about 35 minutes after the graphite flow had been stopped. Friction torque had reached 1.44 inch-pound and after shutdown it was found that the cage had fractured.

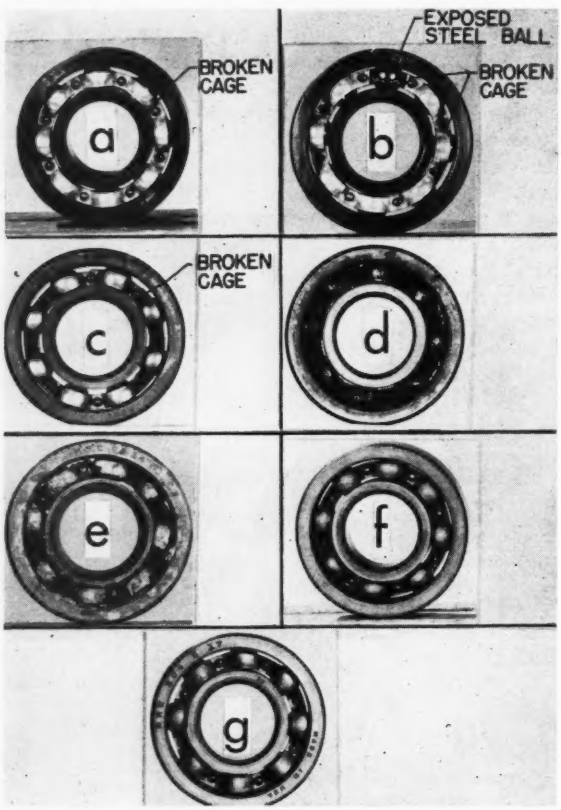

Fig. 6. High temperature bearings after tests. (6a) Test 9, dry, O.P. nitrogen; (6b) Test 16, dry, prepurified nitrogen; (6c) Test 10, 1010 turbine oil, O.P. nitrogen; (6d) Test 13, silicone-diester blend, O.P. nitrogen; (6e) Test 5, MoS_2, air; (6f) Test 7, MoS_2, O.P. nitrogen; (6g) Test 1, graphite, air.

Discussion of Results. Under the conditions of these tests solid lubricants were found to be the best high temperature lubricants. Of all the lubricants tested only graphite provided effective lubrication in an air atmosphere at 1000 F. All five bearings lubricated with graphite ran with low friction torque at 1000 F., and were clean and free after test. Graphite was superior to MoS_2 in air because its oxidation products are harmless whereas those of MoS_2 are abrasive and corrosive. In a nitrogen atmosphere MoS_2 showed none of the deleterious effects which occur in air at temperatures above 700 F., and was an effective lubricant at 1000 F.

In all tests where a nitrogen atmosphere was used, whether with no lubricant, liquid lubricants or solid lubricants, results were better than for the corresponding test in an air atmosphere. Bearings ran longer and to higher temperatures in nitrogen than in air. The maximum temperature reached in each case was higher by at least 150 F. The order of superiority of the lubricants did not change. Solid lubricants were still found to be the best high temperature lubricants in spite of the fact that the silicone-diester blend was effective (from a friction torque standpoint only) to 1000 F. in nitrogen. Bearings run at 1000 F. lubricated with graphite were very clean after test, whereas bearings lubricated with the silicone-diester blend had heavy carbonaceous deposits. After cooling to room temperature, graphite-lubricated bearings remained free and operative, but the silicone-diester-lubricated bearings could not be run because of hardened deposits.

SUMMARY. Lubrication studies of 20 millimeter bore high temperature tool steel ball bearings were made with liquid, and solid lubricants. Liquid and solid lubricants were tested in both air and nitrogen (oil-pumped and prepurified) atmospheres. Liquid lubricants tested were MIL-0-6081A grade 1010 oil and a silicone-diester blend. Solid lubricants tested were molybdenum disulfide and graphite.

Under the conditions of these experiments inert atmospheres were found to be beneficial in every test in which they were used, whether with no lubricant, liquid lubricants, or solid lubricants. Each lubricant tested in both air and nitrogen atmospheres was effective to higher temperatures in nitrogen than in air.

Solid lubricants were found to be better high temperature lubricants than were liquids (in both air and nitrogen atmospheres). All tests in which solid lubricants were used were run to completion at 1000 F. without failure (except MoS_2 in air). Both graphite and MoS_2 provided effective lubrication to 1000 F. (graphite in air and MoS_2 in ni-

trogen). In air MoS_2 lubricated effectively at temperatures of 700 to 850 F., but its oxidation products corroded the bearing cage. A silicone-diester blend lubricated effectively to 1000 F. in a nitrogen atmosphere, but on cooling the bearings became inoperative because of hardened deposits. This is in con-

Table I. Test results. Key: [a]Ref. 8; [b]Inconel cage; [c]Lubricant flow rate for all solids was 0.00002 - 0.00015 lb/min; [d]Lubricant flow rate for liquid lubricants was 0.0003 lb/min.

Test No.	Lubricant	Atmosphere	Max. successful O.R. operating temperature, °F.	Average bearing torque at max. successful temp., in.-lbs.	Total running time, hr.	Remarks
a1	[c]Synthetic graphite	Air	1000	0.08	18.65	Completed 2 hrs. at 1000 F. Bearing very clean & free. Negligible wear.
a2	Dry synthetic graphite	Dry air	1010	0.09	18.5	Completed 2 hrs. at 1000 F. Bearing appearance good. Bearing clean & free.
a,b3	Synthetic graphite	Air	1006	0.13	18.1	Completed 2 hrs. at 1000 F. Bearing in good condition.
a4	Synthetic graphite	Air	996	0.17	18.7	Completed 2 hrs. at 1000 F. Bearing very clean & free.
a5	MoS_2	Air	1001	2.96	19.05	Completed 2 hrs. at 1000 F. Bearing cage badly corroded. Torque very high at end portion of test.
6	MoS_2	Air	738	0.90	16.35	Bearing failed 30 minutes after 2 hr. run at 700 F. Cage broken but not as badly corroded as in test 5.
7	MoS_2	Oil-pumped nitrogen	1000	0.28	2	Ran for 2 hrs. only at 1000 F. Bearing free and in good condition. No oxide of molybdenum present.
8	None	Oil-pumped nitrogen	280	0.10	8.3	Bearing failed. Ran 1 hr. at 400 F. Friction torque reached 1.7 in.-lbs.
9	None	Oil-pumped nitrogen	420	0.84 to 1.16	8.5	Failure. Cage broken. Bearing ran for 29 minutes when being heated from 400 to 550 F. Friction torque at failure reached 2.16 in.-lbs.
10	[d]Mil-O-6081A grade 1010 petroleum oil	Oil-pumped nitrogen	690	0.10 to 0.46	15.5	Failure. Cage broken. Friction torque reached 2.24 in.-lb. at failure. Bearing relatively clean but darkened.
11	Mil-O-6081A grade 1010 petroleum oil	Oil-pumped nitrogen	703	0.09	14.2	Failure but cage not broken. Bearing ran 1 hr. during heating from 700 to 850 F. Friction torque at failure reached 2.36 in.-lb. Bearing clean but darkened.
a12	Mil-O-6081A grade 1010 petroleum oil	Air	538	0.2	14.1	Failure. Cage broken. Torque increased to 5 in.-lb. during heating from 550 to 700 F.
13	Silicone-diester blend	Oil-pumped nitrogen	993	0.2 +	19.9	Bearing completed test at 1000 F. without failure. Heavy carbonaceous deposit in bearing. Bearing turned with difficulty after cooling to room temperature.
14	Silicone-diester blend	Oil-pumped nitrogen	1003	0.2	19.4	Bearing completed test at 1000 F. without failure. Heavy deposit in bearing. Bearing turned with difficulty after cooling to room temperature.
a15	Silicone-diester blend	Air	875	---	16.25	Completed 2 hrs. at 850 F. Bearing heavily coated. Test terminated at this point.
16	None	Prepurified nitrogen	122	0.17 to 0.63	4.0	Failure; cage broken. Bearing ran 1 hr. at 250 F. Friction torque reached 4.9 in.-lb. Bearing very clean.
17	None	Prepurified nitrogen	250	0.07 to 0.95	7.57	Failure. Cage broken. Bearing ran 1.5 hrs. at 400 F. Friction torque reached 2.75 in.-lb.
18	Synthetic graphite	Air	985	0.03 to 0.13	20	Ran for 20 hrs. only at 1000 F. Bearing free and in good condition.
19	Synthetic graphite	Air	980	0.2	2	Ran for 2 hrs. at 1000 F., then lubricant flow was shut off. Bearing ran for 35 minutes after lubricant was shut off. Cage is broken.

trast to the bearings run at 1000 F. with graphite lubrication, which were free after cooling to room temperature.

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(10) G. P. Townsend: "Trends in Design of Aviation Gas Turbine Lubrication Systems." Paper presented at the ASME meeting, Pittsburgh, Pa., June 20-24, 1954.

COMMENTARY, by Dr. H. E. Mahncke (Westinghouse Research Laboratories). It is characteristic of exploratory work of this sort, that it raises more questions than it answers and generally opens up new methods of attack on current problems. The authors are to be commended in that this paper gives us a full measure on both counts.

This paper is a good illustration of the expanded horizon encompassed by the lubrication engineer of today. A few years ago the possibilities of lubricating bearings by the means described here were not even considered. One must include advances in metallurgy also since the three hour life experienced in the dry, air-cooled bearing is in itself an advance over older performance and is a direct reflection of the use of tool steel in place of conventional steel. If one were inclined to be fanciful, and this is a good place for it, speculations would be in order as to how soon the metallurgists will provide us with bearing materials that need no auxiliary lubricant for satisfactory performance under a given set of conditions.

This state of affairs may be a little closer than first glance would indicate. In this connection the authors' observation that cage fracture characterized all the bearing failures in the dry runs is significant. These experiments have very definitely singled out the cage as a weak point in the bearing assembly and emphasized again the need for increased attention to it in order to realize the utmost in the performance of bearing components.

These results are encouraging in another respect. In conventional lubrication of rolling contact bearings, it has not been thought possible to incorporate solid materials with as high shear strength as graphite or molybdenum sulfide in the lubricant and obtain satisfactory performance of precision bearings. The finding that clean bearings were maintained when lubricated with a dust puts a new aspect on the use of solid lubricants in this connection. At the same time another question is brought out by the functioning of specially dried graphite and air. Previous studies have led us to believe that some adsorption of water was required for graphite to exhibit lubricating properties. Perhaps in this case adsorbed oxygen plays the same role. A similar experiment using nitrogen as the carrier for graphite suggests itself as possibly shedding some further light on this point.

Turning now to another facet of this work, namely the lubricants, it is significant to note that with all the organic liquids used, carbonaceous deposits were obtained, though not much in some cases. This indicates, particularly with the nitrogen atmosphere, that pyrolysis or thermal decomposition of the lubricants is occurring to an increasing extent. It also emphasizes the fact that we must reckon with thermal stability as differentiated from resistance to oxidation in our consideration of high temperature lubrication problems. Indeed, it is possible that a lesser stability might be an advantage here since more complete decomposition could conceivably contribute to keeping the bearing clean. Here again, another type of experiment suggests itself. In many oxidation reactions we have the empirical 10 degree rule applying, i.e., rate of reaction doubles for temperature rise of approximately 10 C., though we have recently found cause to doubt the applicability to grease oxidation. Experiments of the sort just described, if run at constant temperatures, could supply us with some valuable information as to how the strictly thermal reactions were governed by temperature.

The specific data that the authors have cited also gives rise to several questions. In my opinion the following ones come foremost:

1. What was the rate of gas flow through the bearings? The small differences in running friction suggest the possibility that increased mass flow when the lubricants were used might have some cooling effect on the bearings aside from their function as lubricants. This, of course, leads to the next question:

2. How did bearing temperatures compare with ambient?

3. Was any permanent growth noted in the bearings as a result of exposure to these temperatures?

4. Do the authors have any idea as to the ultimate life that might be expected from these bearings when lubricated at 1000 F. with air and graphite or with molybdenum disulfide and nitrogen?

AUTHORS' CLOSURE. The rate of gas flow to the bearings was between 0.05 and 0.25 cubic feet per minute. To obtain an effective solid-gas-mist or dust, it was necessary to increase the gas flow as the fine solid particles were used up; the coarser particles remaining required more vigorous agitation, therefore greater flow. With both liquid lubrication and dry operation the gas flow was 0.12 cubic feet per minute.

It is felt that the cooling effect on the bearings by the increased mass flow when the lubricants were used was small and that the small differences in running friction could not be due to this factor. Bearing outer race temperature was held constant, at any rate, at a given temperature setting by controlling the ambient furnace temperature. This method gave the best results. The bearing inner race temperature, however, was not controlled and was lower than the outer race temperature by 60 to 100 F.

The inner race was cooler probably because of the heat loss through the shaft rather than because of the cooling effect of the gas or lubricant. The fact that the inner race

was cooler was favorable since there was no danger of losing clearance and thus preloading the bearing. The ambient temperature was very close to the bearing outer race temperature and was not more than 50 F. greater during equilibrium conditions.

Measurements of components of the bearings were not made before test because non-destructive disassembly of the bearings was not possible. Therefore permanent growth could not be determined by measurement after test. However, qualitatively speaking, permanent growth was not evident since bearing housing fits and internal radial clearances were about the same before and after test.

Our tests were limited to a maximum of 20 hours so that an accurate prediction of the ultimate life that might be expected from these bearings when lubricated at 1000 F. with air and graphite or with molybdenum disulfide and nitrogen is not possible. However, no wear could be discerned by visual inspection of these bearings after test, and their general condition after test was comparable to that before test.

Dr. Mahncke's comments on the weakness of the cage are well taken. Not only these experiments but other bearing tests as well point out the general weakness of the cage as a bearing component part. Research on both cage materials and designs is being done at this and other laboratories. (Z. N. Nemeth)

Patent Abstracts

(Compiled by Ann Burchick, Aluminum Company of America.)

Stable Fuel Oil Compositions, Patent #2,697,033 (H. A. Ambrose & O. L. Brandes, assignors to Gulf Research & Development Co.) A fuel oil composition comprising a major proportion of a mixture of straight run and catalytically cracked distillate fuel oils tending to deposit sludge, wherein the straight run and catalytically cracked fuel oils are present in a volume ratio of between about 9:1 and about 1:9, and containing a small amount of a combination of a member selected from the group consisting of the zinc, barium, calcium, and magnesium salts of a dialkyl dithiophosphoric acid in which the alkyl groups contain 4 to 12 carbon atoms and a member selected from the group consisting of the barium and calcium salts of oil-soluble petroleum sulfonic acids, said small amount being sufficient to inhibit sludge deposition from said mixture of oils and comprising at least 0.005 per cent by weight of said mixture of oils of each of said salt of said dialkyl dithiophosphoric acid and said salt of said oil-soluble petroleum sulfonic acids and not more than 0.25 per cent of said combination by weight of said mixture of oils.

Emulsion Type Drawing Compounds Containing Carboxyalkyl Cellulose Salts, Patent #2,697,072 (H. Roden, assignor to The Texas Co.) An improved lubricating composition for metal working which consists essentially of an aqueous emulsion of a naphthene base lubricating oil having an SUS viscosity at 100 F. of about 275 to 325, containing about 5 to 20 per cent by weight based on the weight of the composition of a soap obtained by saponifying wool grease with a small excess of alkali, about 10 to 70 per cent by weight based on the weight of the composition of finely divided calcium carbonate, about 0.1 to 1 per cent by weight based on the weight of the composition of sodium carboxymethyl cellulose, and about 0.5 to 10 per cent by weight based on the weight of the composition of water.

Turbine Oil Antioxidants, Patent #2,697,073 (R. V. White & H. D. Norris, assignors to Socony-Vacuum Oil Co., Inc.) A mineral lubricating oil containing a small amount, sufficient to inhibit the oxidation tendencies thereof, of the reaction product obtained.

Treatment of Hydrocarbon Oils, Patent #2,697,683 (W. F. Engel & H. Hoog, assignors to Shell Development Co.) A process for treating sulfur-bearing hydrocarbon oils which comprises contacting a sulfur-bearing hydrocarbon oil of unsaturated nature under hydrogenation conditions at a pressure of at least 10 atmospheres and at a temperature between 350 C. and 500 C. in the presence of an added gas consisting largely of hydrogen with an impregnated type molybdenum oxide catalyst consisting essentially of an alumina carrier which catalyst has been treated with a strong inorganic acid for at least 16 hours at a temperature of about 90 C. and impregnated with from 4 to 8% molybdenum and about 12% cobalt and between about 2.5 and 25% of potassium each based on the molybdenum, said catalyst having been calcined in the presence of oxygen at a temperature of from about 700 C. to about 800 C. for a period of from 2 to about 40 hours.

Manufacture of Lithium Hydroxy Carboxylic Acid Soap Greases, Patent #2,697,693 (G. V. Browning, L. C. Brunstrum & W. L. Hayne, Jr., assignors to Standard Oil Co.) A method of producing a grease comprising a lubricant base and a lithium soap of an organic acid substance selected from the group consisting of hydrogenated castor oil and hydroxy fatty acids of at least 12 carbon atoms wherein the hydroxyl group is separated from the carboxyl group by at least one carbon atom, which method comprises subjecting a mixture comprising lubricant base, lithium hydroxy soap constituents and at least 1 per cent of water to a temperature of at least about 275 F. and superatmospheric pressure, agitating said mixture, relieving the pressure after the mixture has reached said temperature by venting the steam therefrom, and maintaining said mixture at substantially said temperature while venting said steam.

Process for Preparing Lubricating Oil Additive and Products, Patent #2,698,296 (J. M. Musselman & R. E. Knowlton, assignors to The Standard Oil Co.) An oil-soluble lubricating oil detergent additive having a high alkaline reserve adapting it for use in engines consuming high sulfur content fuels comprising the second stage saponification product of an alkyl phenol, an alkaline earth hydroxide and the primary partial saponification product of an alkaline earth hydroxide and the product of the reaction at a temperature below sludge formation of a phosphorus sulfide and degras.

Grease Compositions Containing Synthetic Gelling Agents, Patent #2,698,297 (J. J. Giammaria, assignor to Socony-Vacuum Oil Co., Inc.) A grease comprising an oleaginous vehicle and a salt in an amount sufficient to thicken said vehicle to form a grease, said salt being a metal salt of an acidic reaction product obtained by reaction of a compound selected from the group consisting of an aliphatic monohydric alcohol having at least about eight carbon atoms per molecule and an aliphatic monamine having at least about eight carbon atoms per molecule, with an acidic copolymer of an alpha beta unsaturated polycarboxylic acid and a low molecular weight organic compond having a terminal vinyl group and having less than about ten carbon atoms per molecule, such that from about fifty to about ninety per cent of the carboxyl groups of the acidic copolymer are reacted with said compound, said acidic copolymer having a molecular weight above about 1,000, the metal of said salt being selected from the group consisting of metals of groups I through III of Mendeleeff's periodic system.

(Continued on Page 285)

Experiment & Experience

Detecting Bearing Failures By Measuring Temperature Acceleration, by W. C. Schmidt & W. J. Anderson, NACA Lewis Flight Propulsion Laboratory, 21000 Brookpark Rd., Cleveland 11, Ohio.

One of the problems in bearing research, when bearings are operated at conditions which may produce failure, is how to detect a failure before it becomes catastrophic. If an incipient failure can be detected early enough, a total failure can often times be avoided and valuable information on the cause of failure can be obtained.

Standard methods for detecting failure include motor torque rise, temperature rise and increase in friction torque or vibration. Measurement of friction torque is difficult under severe operating conditions. Vibration is valuable in detecting fatigue but not usually in detecting lubrication failures which may result in seizure. Motor torque and bearing temperatures begin to rise when an incipient failure occurs but often not fast enough to prevent a catastrophe. In contrast to the slow response of temperature, the second derivative of the temperature with respect to time (the acceleration) reaches a high positive value before significant temperature changes are noticed.

An instrument for measuring the magnitude and sign of temperature acceleration has been developed at the NACA Lewis Flight Propulsion Laboratory, Cleveland, Ohio. The instrument employs a modified servo-driven self-balancing potentiometer system which functions as an electromechanical D.C. amplifier to amplify the small voltages from the thermocouple at the bearing. These amplified voltages are then differentiated twice by two cascaded R-C networks. The network output voltage, which is proportional to the second derivative of the thermocouple input voltage, is indicated on a meter. The output voltage can be used to operate a warning device or shut down the rig automatically when the temperature acceleration reaches a preset magnitude.

The instrument is doubly valuable because it will not only detect a failure when a bearing is being run at constant conditions, but it will also predict whether or not a bearing is approaching an equilibrium condition or a failure after the operating conditions have been made more severe. Negative acceleration indicates an approaching equilibrium, positive acceleration an imminent failure.

Fig. 1 illustrates the sequence of events that occurred when the operating speed of a 75 mm bore roller bearing was increased from 4,000 to 16,000 rpm. Plots of acceleration with time (Fig. 1a) and of temperature with time (Fig. 1b) are shown. The time axes of both curves were synchronized. Before any perceptible change in temperature is noticed the acceleration has reached a maximum and is decreasing toward zero. After 22 seconds the acceleration becomes negative, indicating an approaching equilibrium.

To check the effectiveness of the instrument in detecting failure a similar roller bearing operating at 18,000 rpm was used. Incipient failures were produced by shutting off the oil flow. When the acceleration had reached a large positive value, oil flow was resumed. Fig. 2 illustrates a typical acceleration pattern during the oil interruption. Using this method the bearing was subjected to four incipient failures without a total failure resulting. In each case motor torque and noise level had begun to rise be-

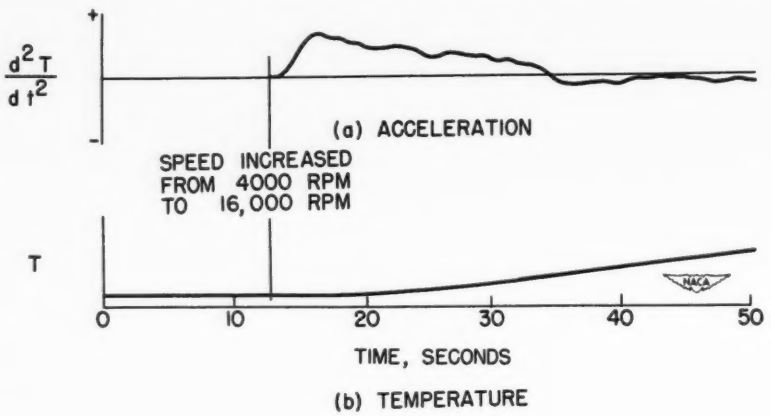


Fig. 1. Temperature and temperature acceleration patterns during an increase in severity of operating conditions. (Fig. 1a, top portion; Fig. 1b, bottom portion.)

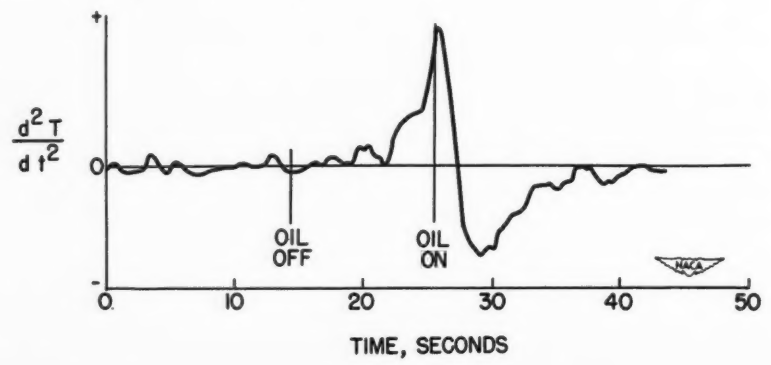
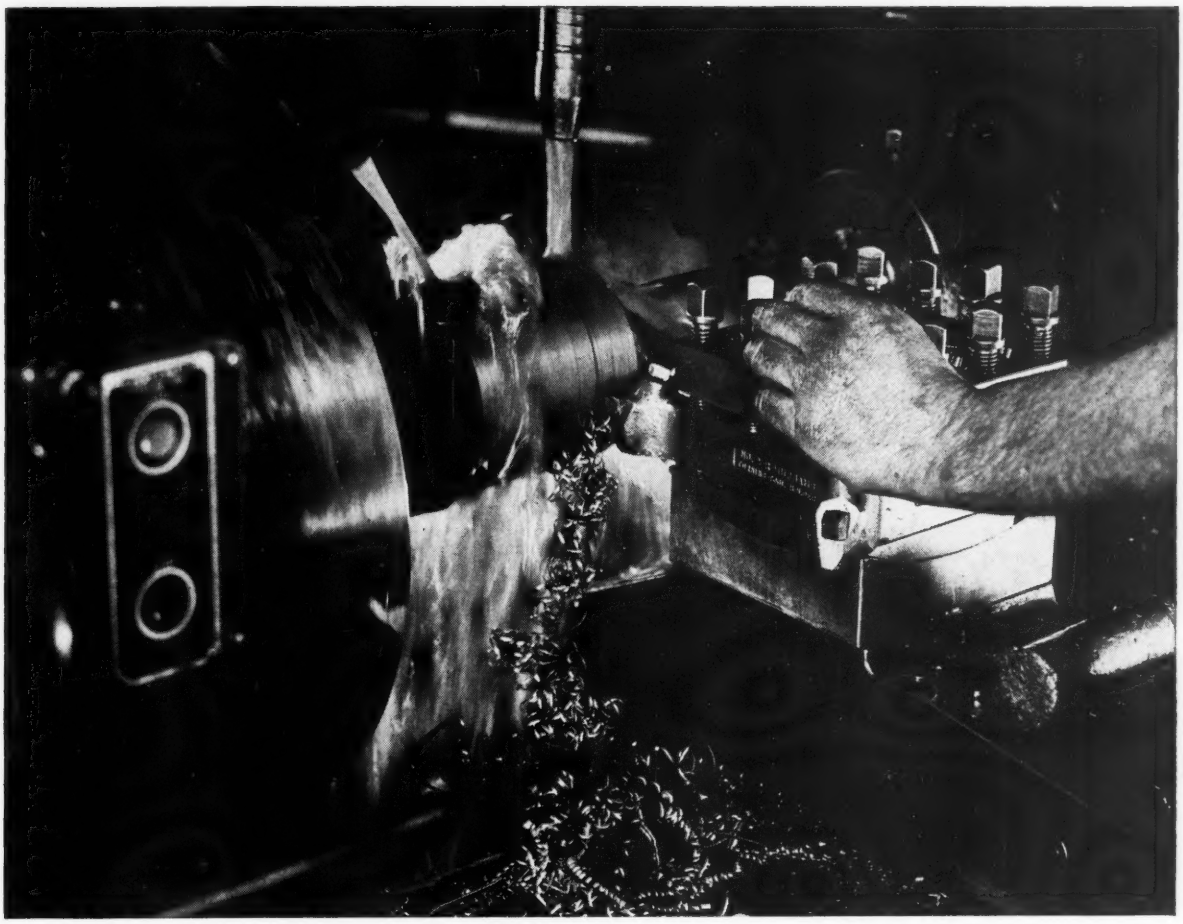


Fig. 2. Temperature acceleration pattern during an incipient failure.



LIQUID DRESINATE® EMULSIFIER IMPROVES HARD WATER STABILITY

Soluble cutting oils, especially those used in hard water areas, offer two advantages when made with liquid Dresinate. Blends of this Hercules emulsifier with petroleum sulfonate improve emulsion stability over a wide range of water conditions and concentrations, and, in most cases, cut compounding costs.

Economies in plant equipment and manpower needs are made possible through the use of a liquid Dresinate. These low viscosity, high solids emulsifiers are manufactured to exacting standards assuring product uniformity from shipment to shipment.

Liquid Dresinate, available in a number of different types, is described in a recent booklet. This booklet also contains suggested formulations and information regarding selection of the correct Dresinate for emulsion-type oils used in metal working and other fields. Write Hercules Powder Company for your copy.

Industrial Chemicals—PMC Dept.

HERCULES POWDER COMPANY

INCORPORATED

979 Market Street, Wilmington 99, Delaware

P155-1

fore the oil flow was resumed, but these trouble signs lagged behind acceleration.

(Section News, from Page 254)

the present classification systems (SAE, ASTM, etc.), and then presented his proposal for a new system. (Submitted by D. W. Howard, Publicity Chrmn.)

TWIN CITIES, May. Dr. H. E. Mahncke, Westinghouse Research Labs., presented a paper entitled "Lubricants Research—Consumer's Viewpoint," which included references to design, new applications, basic knowledge, plus a bonus on mechanisms of solid lubricants. (Submitted by C. D. Johnson, Sec'y.)

WHEELING, May. Election of Officers (see ASLE Directory.)

June. Annual Picnic, with the ASLE Pittsburgh Section invited as guests. (Submitted by S. J. Litten, Sec'y-Treas.)

(New Products, from Page 237)

with the use of a simple regulating screw, accomplishing positive delivery without throttling. This results in a constant and uniform delivery even when lubricants of different grades of viscosity are used. Designed for a rotary drive, the gear pump is small and compact, measuring but 2⅝" x 3⅛" x 3½"; it is sturdily built and may be adjusted by hand or automatically in stages of 1½ gallons per hour. (Nathan Mfg. Corp., LE-11/4, 45-02 Ditmars Blvd., Long Island City 5, N. Y.)

Solvent Recovery Still. Featured in the redesigned solvent recovery still is the use of the "RS" three-heat hot plate which permits rapid heating until distillation begins, and reduction of the heat thereafter to maintain the desired distillation rate. Vapor-locking is prevented by passing the raw solvent feed-line through the water-cooled condenser; vapors passing up the feed-line are condensed and refluxed back into the retort. Designed primarily for easy, economical recovery of carbon tetrachloride used in the determination of the bitumen content of asphaltic pavement mixtures, the solvent recovery still also finds wide application in the recovery and purification of other valuable used solvents such as petroleum ether, benzol, gasoline, alcohol, and other extraction vehicles. (Precision Scientific Co., LE-11/4, 3737 W. Cortland St., Chicago 47, Ill.)

Portable Air-Operated Power Gun. A new, portable air-operated power gun (Model 711-H), said to save 6 man-hours for every 25-lb. pail of lubricant applied, and versatile enough to power-lubricate any machine in the automotive, farm, and industrial fields, pumps directly from original 25- or 35-lb. pails of lubricant. Delivering up to 14½ ounces of lubricant per minute, a 6-ft. high pressure hose, "Z" swivel, and control valve provide complete convenience of operation. Economies in handling lubricants are realized in that transferring and loading operations are completely eliminated: a follower plate cleans all of the grease out of the pail with no waste; and an easily applied cover, which adjusts to either 25- or 35-lb. pails, completely seals the lubricant against dirt and contamination. A socket to hold the control valve when not in use is conveniently located on the cover; a rubber-grip handle increases the utility of this fully portable unit which weighs only 12½ pounds. (Alemite Div., Stewart-Warner Corp., LE-11/4, 1828 W. Diversey Blvd., Chicago 14, Ill.)

Molykote 165X, a recently developed open gear lubricant for application on highly loaded gears which normally can only be lubricated infrequently, is a near-colloidal dispersion of Molykote Microsize in a viscous tacky, and adhesive petroleum oil which has been rendered fluid by the addition of a volatile non-flammable diluent. The evaporation of the diluent leaves a plastic film that does not tend to hold dust and strongly resists being washed off

BENTONE* 34
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THE ACME REFINING CO., Cleveland, Ohio
ADAM COOKS SONS, INC., Linden, N. J.
ALEMITE DIV., STEWART-WARNER CORP., Chicago, Ill.
ALLUBE CORP., Glendale, Calif.
THE AMERICAN LUBRICANTS CO., Dayton, Ohio
ARKANSAS FUEL OIL CORP., Shreveport, La.
BATTENFELD GREASE & OIL CORP., Kansas City, Mo.
BATTENFELD GREASE & OIL CORP. OF NEW YORK, North Tonawanda, N. Y.
BEL-RAY CO., INC., Madison, N. J.
THE BROOKS OIL CO., Pittsburgh, Pa.
CASCADE PETROLEUM CO., Denver, Colo.
CATO OIL AND GREASE CO., Oklahoma City, Okla.
CONSUMERS COOPERATIVE ASSOCIATION, Kansas City, Mo.
CRAWFORD EMULSIONS, Pittsburgh, Pa.
DENS-OIL LUBRICANT CO., Kansas City, Mo.
JAMES W. DOYLE CORP., Detroit, Mich.
FISKE BROTHERS REFINING CO., Newark, N. J.
FISKE BROTHERS REFINING CO., Toledo, Ohio
THE FRANKLIN OIL AND GAS CO., Bedford, Ohio
GEORGIA-CAROLINA OIL CO., Macon, Georgia
GLOBE GREASE & MFG. CO., Los Angeles, Calif.
GOPLERUD LUBRICANTS CO., Mason City, Iowa
GREDAG, INC., Niagara Falls, N. Y.
HI-WAY REFINERIES, LTD., Regina, Sask., Canada
THE HODSON CORP., Chicago, Ill.
E. F. HOUGHTON & CO., Philadelphia, Pa.
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INTER-STATE OIL CO., Kansas City, Kansas
KEYSTONE LUBRICATING CO., Philadelphia, Pa.
LUBRICATION CO. OF AMERICA, Los Angeles, Calif.
MacMILLAN OIL CO. OF ALLENTOWN, Allentown, Pa.
MAGIE BROTHERS, INC., Chicago, Ill.
MAGNUS CHEMICAL CO., Garwood, N. J.
MANITOBA CO-OPERATIVE WHOLESALE LTD., Winnipeg, Man., Canada
METALCOTE OIL CO., St. Paul, Minn.
MID-STATES LUBRICANTS, Kansas City, Mo.
MIDWEST OIL CO., Minneapolis, Minn.
THE OHIO GREASE COMPANY, Loudonville, Ohio
OIL DISTRIBUTORS OF PHILADELPHIA, Philadelphia, Pa.
ONYX INTERNATIONAL, Jersey City, N. J.
PANTHER OIL & GREASE MFG. CO., Fort Worth, Texas
PANTHER OIL & GREASE MFG. CO. OF CANADA, Toronto, Ontario, Canada
PENN-CREST OIL & GREASE CORP., Long Island City, N. Y.
PENN PRODUCTS CO., DuBois, Pa.
PHOENIX OIL COMPANY, Augusta, Ga.
A. B. PLATING SUPPLY COMPANY, Milwaukee, Wis.
PRAIRIE STATES OIL & GREASE CO., Danville, Ill.
PRECISION BEARING & TRANSMISSION CO., Omaha, Nebr.
RILEY BROS., INC., Burlington, Iowa
SASKATCHEWAN FEDERATED COOP. LTD., Regina, Sask., Canada
SERVICE LUBRICANTS, INC., Chicago, Ill.
L. SONNEBORN SONS, INC., New York, N. Y.
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SOUTHWESTERN PETROLEUM CO., Fort Worth, Texas
SPECIALTY PRODUCTS CO., Jersey City, N. J.
SUNLAND REFINING CORP., Fresno, Calif.
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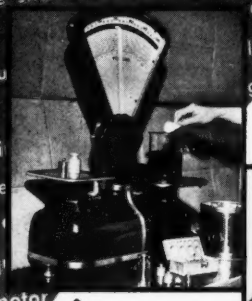
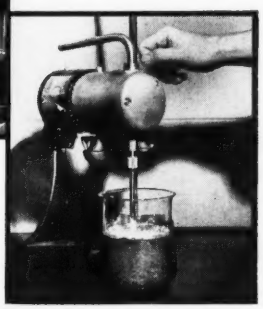
NATIONAL LEAD CO.
BAROID DIVISION
P. O. Box 1675, Houston 1, Texas

Bentone* 34 Grease Multi-Tested for a Thousand Uses!

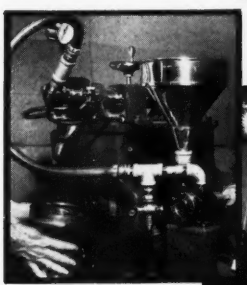


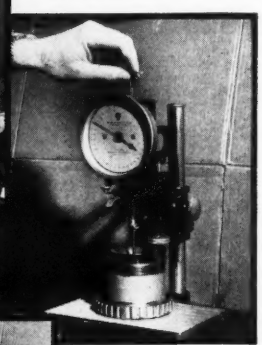
EXACT FORMULATION — various formulas are tested until one is produced that meets all of manufacturer's requirements.



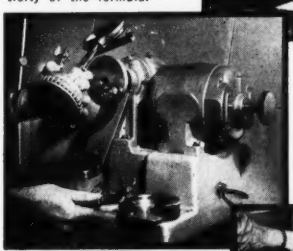
MIXING—mixing prepares formula for milling.

MILLING—milling or homogenizing produces a smooth, consistently uniform grease.

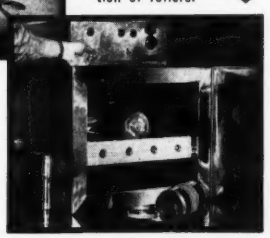




EXACT CONSISTENCY — penetrometer tests indicate consistency or hardness of grease sample and determine the plasticity of the formula.



EXCELLENT MECHANICAL STABILITY — roller tests measure mechanical stability of grease and produce a numerical evaluation — during penetration testing — of the change in consistency caused by kneading or working action of rollers.



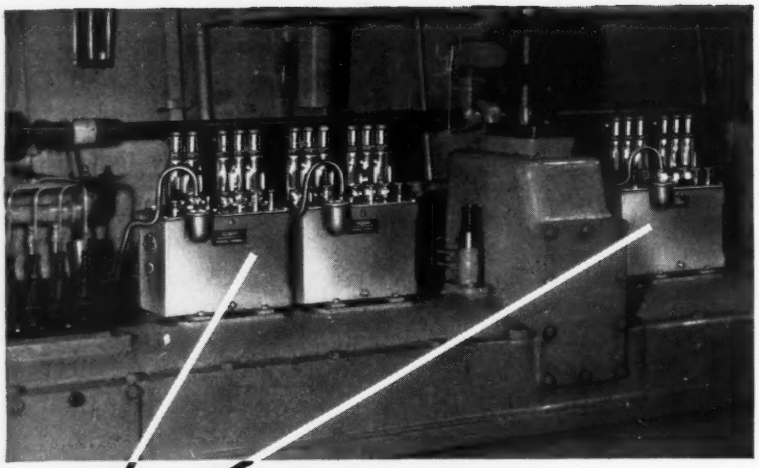
HIGH SHEAR STABILITY—shear stability tests exert influence far in excess of any working pressures for which grease will be used.

EVERY DAY Baroid's extensive laboratories assist grease compounders to formulate greases with Bentone* 34 gelling agents. Compounders throughout the country have used Baroid laboratory service to obtain the best formula — using *their* oil and Bentone* 34 — to make a grease that's right for thousands of applications. For the farm . . . automotive industry . . . industrial machinery of every kind — grease made with Bentone* 34 serves a need not met by any other type of lubrication. Its unique composition has a tenacious quality that causes it to adhere to metal . . . has a matchless resistance against rain and washout . . . works well under both *extreme* high and low temperatures! It answers a multitude of lubrication problems because one Bentone grease is good for scores more applications than any known conventional lubricant.

Bentone grease is always uniform, always the same high quality. Write today for illustrated brochure about Bentone* 34 gelling agent.

BENTONE* 34

THE NON-SOAP GELLING AGENT



MANZEL

FORCE FEED LUBRICATORS Control Lubrication to Save Oil and Cut Production Losses

Outdated lubrication practices can waste half, or more, of all the lubricants you buy. Only the exact amounts needed — never more and never less — are used with Manzel Force Feed Lubricators. There's no waste!

And because Manzel Lubricators operate dependably and automatically without thought or attention, they save labor and the cost of unexpected breakdowns caused by faulty or neglected lubrication. They quickly pay for themselves and then keep on saving money through the years.

Can be built into new, or installed on existing equipment. On any question of how best to lubricate, always call or write Manzel.

SPECIAL QUALITY FEATURES OF MANZEL LUBRICATORS

- Completely protected with Parco Lubrite
- Rust resistant reservoirs
- Closer fitting plungers made possible by special precision equipment
- Gears of harder alloy for longer wear
- Every unit factory-tested before shipment

FOR CHEMICAL FEEDERS, TOO, CONSULT MANZEL

Professionally qualified engineering representatives throughout the country.

Manzel

DIVISION OF
HOUDAILLE-HERSHEY CORP.
273 BABCOCK ST., BUFFALO 10, N. Y.

by water. The film will not crack or peel off at temperatures as low as 0°F. Particularly useful where only one or two gears of a long gear train are exposed and lubrication of the train must be achieved through the transfer of lubrication from gear to gear, it may be applied by brushing, pouring, drop-feed cups, spray gun, or mechanical force-feed lubricators. (The Alpha Molykote Corp., LE-11/4, 65 Harvard Ave., Stamford, Conn.)

Powdered Lubricant. Acrawax C Atomized, an extremely finely powdered lubricant that gives efficient lubrication of metal-to-metal parts which are very tight fitting or where force fits are needed, can be applied by dusting or dipping the screw part into it. (The small amount held on the surface of the metal gives the desired lubrication.) Non-tacky, non-corrosive, insoluble in water, oil, and solvents, it has a melting point of 285 F. (140 C.) and is a good dielectric. (Glyco Products Co., Inc., LE-11/4, Empire State Bldg., N. Y. 1, N. Y.)

'BB-21A Mechanipak Seal,' a mechanical seal specifically designed for use on rotary shafts at pressures up to 150 psi, has been announced that is furnished completely assembled, ready to install. Standard construction includes brass shell, brass washer, and Buna-N bellows; seals are available for shafts from ⅜" to 3" diameters. (Buna-N or neoprene bellows are furnished for operating temperatures up to 212 F. and pressures up to 150 psi; silicone bellows are provided for temperatures up to 400 F. where pressures do not exceed 50 psi.) (The Garlock Packing Co., LE-11/4, Palmyra, N. Y.)

'Clear-Vue' Distillator, a major new development in distillation apparatus, features a quarter-turn condenser tube which permits the distillation shield to be set flush with the condenser. (This construction permits complete unobstructed observation of all receiving flasks; allows operator to make more accurate tests.) Other features include: Add-A-

Unit construction (allowing any number of units to be coupled together; if service is needed, any unit can be removed without disturbing the others); shield with heat-treated observation window and built-in flash height adjustment; powerstat control of electric heater; stainless steel interior and exterior; 2" insulated condenser; and ice or mechanical refrigeration. Multiple banks of distillator can be arranged for one up to 100 units. (Labline Inc., LE-11/4, 217 Desplaines, Chicago, Ill.)

Anti-Seize & Sealing Dispersion. A new graphite product, "dag" Dispersion No. 217, has been developed specifically as an anti-seize and sealant for high-pressure oxygen systems where line pressures reach 2000 psi. Available in 4-ounce tubes, 2-lb. jars, 13- & 16-lb. pails, and in 390-lb. drums, it possesses positive anti-seize properties at oxygen pressures as high as 2,000 psi and at temperatures ranging from 160 F. to —65 F. It is completely non-inflammable, even in the presence of high-pressure oxygen at temperatures of 575 F. and higher. (Acheson Colloids Co., LE-11/4, 1630 Washington Ave., Port Huron, Mich.)

Micro-Fog Lubricators. To extend the advantages of Micro-Fog lubrication to a wider range of bearing applications, Norgren has added five new models to its line. A new 1-qt. oil reservoir lubricator is available in ¼", ¾", and 1" pipe sizes with capacities to lubricate up to 32, 200, and 300 bearing inches, respectively. The 4½ gallon model is now being made in ¾" and 1" sizes with 200 and 300 bearing inch ratings. The ¼" lubricator at rated operating pressure of 20 psi uses 2 cfm of air; the ¾" at 23 psi uses 5 cfm; and the 1" at 40 psi uses 7½" cfm. (C. A. Norgren Co., LE-11/4, 3434 S. Elati, Englewood, Colo.)

A.S.L.E.
Lapel or Charm Emblems

ASLE insignia emblems (of raised polished gold on a satin-finish background of gold-filled construction) are available to members in lapel pin, button, or charm styles at $3.75 ea. postpaid. To order, indicate type desired, fill in your name and address, enclose remittance, and mail to:

ASLE, 84 E. Randolph St.
Chicago 1, Illinois

Pin____ Button____ Charm____

Name_____

Address_____

_____
(Please Print)

(Current Literature, from p. 266)

Creative Engineering Service free in consultation with any company's designers or engineers on any filtration problem. (Permanent Filter Corp., LE-11/4, 1800 W. Washington Blvd., Los Angeles 7, Calif.)

"Trabon Lubrication for Machine Tools." Bulletin 5410 outlines automatic lubrication systems made by the company for use on machine tools. On-the-job applications and various components are illustrated. (Trabon Engineering Corp., LE-11/4, 1814 E. 40th St., Cleveland 3, Ohio).

"'dag' Colloidal Graphite for Assembly & Run-in of Engines & Machinery." Bulletin 421 contains photographs, diagrams, charts, and information on the advantages offered by colloidal graphite in the assembly and run-in of machines, and shows how to use colloidal graphite chiefly in the form of a petroleum oil dispersion. (Acheson Colloids Co., LE-11/4, 1630 Washington

UCON
TRADE-MARK
LUBRICANTS

for MISSISSIPPI CHEMICAL CORPORATION

POWER RECOVERY ENGINES in Mississippi Chemical's ammonia oxidation plant have operated on UCON synthetic Lubricants for *more than a year* at 460°F. without a shutdown. With petroleum oil, maximum operating temperature was 400°F., and the engines had to be dismantled every month or two for cleaning and carbon removal.

Higher temperatures mean more recovered power; elimination of down-time means higher production; and reduced maintenance means savings.

UCON Lubricants have outstanding resistance to sludging and carbonizing. Check them for power recovery engines, compressors, vacuum pumps—and for general industrial lubrication. Write today for complete information.

CARBIDE AND CARBON CHEMICALS

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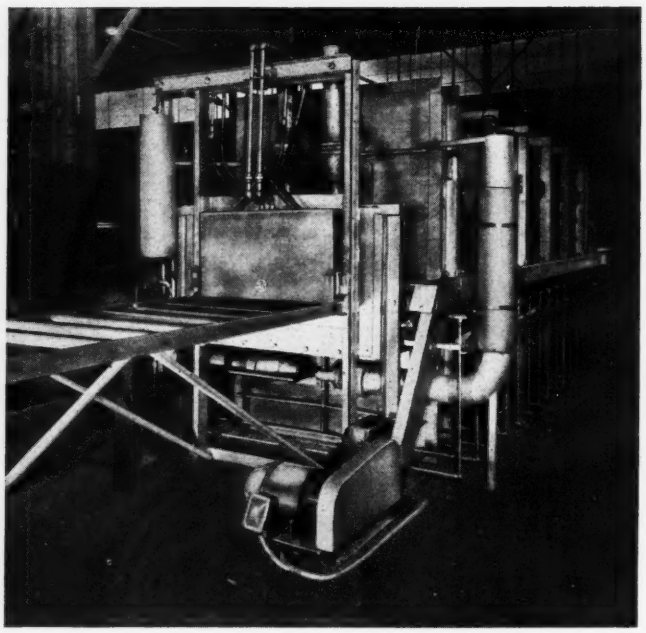
"Ucon" is a registered trade-mark of UCC.

use 'dag' dry films for trouble-free lubrication



Here's how a Cleveland foundry proved the value of 'dag' *dry-film lubrication* in the operation of its continuous core-oven conveyor . . .

A 'dag' Colloidal Graphite dispersion was used in place of powdered graphite. The lubrication interval of conveyor chain and rollers was extended from *four* days to *sixty* days! In addition to tremendous lubricant and labor savings, conveyor wear has been notably reduced, carbon formation and flake-off eliminated.

This is typical of the extreme-temperature problems solved by 'dag' dispersions . . . problems with kiln cars and hot-strip mills . . . problems with *any* moving parts subjected to temperature extremes . . . problems where solvent action in degreasers or other situations destroys conventional lubricants.

You'll find a surprising number of ways to use 'dag' dispersions described in our free booklets. Write today for Bulletins No. 424-S7 and No. 435-S7.

Dispersions of molybdenum disulfide are available in various carriers. We are also equipped to do custom dispersing of solids in a wide variety of carriers.

Use 'dag' colloidal graphite to stretch maintenance dollars over 1400 percent!

ACHESON COLLOIDS COMPANY

PORT HURON, MICHIGAN

...also ACHESON COLLOIDS LIMITED, LONDON, ENGLAND

Ave., Port Huron, Mich.)

"ASTM Proceedings." The '54 edition, recently published, records the technical accmplishments of the American Society for Testing Materials for 1954. Leading the volume is the Summary of the Proceedings of the 57th Annual Meeting (held in June '54), listing by title and author the program for each of the 36 sessions. Reports of the technical committees (of which there are 68) and their appendices provide a wealth of useful technical information, as do the 37 technical papers and discussions on a wide variety of subjects pertaining to research and testing of materials. (A S T M, LE-11/4, 1916 Race St., Philadelphia 3, Pa.; price $12.00 per copy.)

Redesigned Senior 'Titra-Lite.' Data Sheet 11508 describes the uses and features of the redesigned senior 'titra-lite' (a titration stand providing evenly diffused daylight illumination for both the titration burettes and flasks), including the use of the full-view burette clamp which holds the burette firmly without danger of breaking while allowing markings to remain fully visible. (Precision Scientific Co., LE-11/4, 3737 W. Cortland St., Chicago 47, Ill.)

Electrical & Lubricating Devices. Catalog No. 55, recently released, contains complete descriptive data on all Trico electrical and lubricating devices. Products are profusely illustrated; catalog numbers, sizes, general engineering data, and ordering information (including list price information) are clearly shown. (Trico Fuse Mfg. Co., LE-11/4, 2948 N. 5th St., Milwaukee 12, Wisc.)

Revised JIC Pneumatic Standards. Complete, unabridged, revised-up-to-date copies of the JIC Pneumatic Standards for Industrial Equipment, incorporating all revisions made in the January '55 meeting of the Joint Industry Conference, are now available. The revised edition contains a word-for-word reprint of the Standards, two pages of graphical symbols, a sample pneumatic circuit employing these symbols, a glossary of terms used, and other interesting information. (Miller Fluid Power Co., LE-11/4, 2040 N. Hawthorne Ave., Melrose, Park, Ill.)

Parker Accumulators & Accessories. Catalog 1536 gives complete information on Parker piston-type accumulators (highly suitable for storing energy, absorbing shock, and supplementing pump capacity in hydraulic systems on a wide variety of industrial equipment) and the newly announced pre-charging accessories (including gages, adapter, gaging device, hose, and charging assembly). The accumulator line includes 11 sizes, ranging in capacity from 10 to 1155 cubic inches; rating working pressure is 3000 psi. (Parker Appliance Co., LE-11/4, 17325 Euclid Ave., Cleveland 12, Ohio.)

new! ADVANCED ENGINEERING FEATURES

new! EXTRA-HIGH FLOW RATES

new! QUICK OPENING LIDS

announcing

A COMPLETE NEW LINE OF HONAN-CRANE

OIL FILTERS

...the first in a series of important engineering developments by the NEW Corporation ... HOUDAILLE-HERSHEY OF INDIANA, INC.

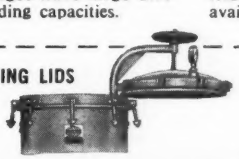
FULL FLOW—For in-line installation at high flow rates—25 to 800 GPM. Low pressure drop—only 4 PSI across unit at 170 SUS. Uses new "FLO-PAC" pleated paper cartridge permitting full flow of oil—removal of particles down to one micron.

MULTI-CARTRIDGE Eleven sizes to choose from with six different types of cartridge filter elements to give exact degree of filtration needed. New "FLO-PAC" and "KLEER-PAC" cartridges have large dirt holding capacities.

BULK REFILL—For absolutely clean oil—bulk Cranite filtering medium provides thorough depth type purification, removing all solids and products of oxidation in solution. Bulk or cartridge type cellulose refills available for fine filtering.

ALL MODELS HAVE QUICK-OPENING LIDS

Purifier lid is fastened with swing bolts which one man can loosen quickly. Lid swings back for easy access to refills.



Write for engineering bulletins and quotations on all three models.

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CRESOL

ADDITIVES

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in the preparation of:

Cutting Oils
Drawing Oils
Grinding Oils
Metal Working Oils
Engine & Heating Fuels
Rust Preventives

For
Exceptional Performance
at Low Cost
use

- CRESOL Z-1, for EP Gear Oils, Cutting Oils, Drawing and Stamping Oils
- CRESOL Z-2, for Cutting Oils, Grinding Oils
- CRESOL Z-3, for EP Lubricants, Drawing Compounds
- CRESOL Z-4, for Soluble Drawing Oils and Cutting Oils
- CRESOL Z-5, Oxidation Inhibitor for Lubricating Oils
- CRESOL Z-7, for Automatic Transmission Fluids
- CRESOL Z-51, for Rust Preventives (Oil and Solvent Type), Lubricity Agent for Lubricating Oils, Fatty Oil Replacement
- CRESOL 22-C, Engine and Heating Oil Additive to prevent carbon deposits

Samples, and suggested formulae for general or specific applications, available upon request.

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Alpha "Field Report No. 138a," features a 24,000:1 magnification electron microscope photograph of molybdenum disulfide flakes, as well as photos of various molybdenum disulfide products at a 200 times magnification. Reputedly the first large magnification electron micrograph of MoS_2, the photo shows particles (invisible to the naked eye), the hexagonl structure of the crystals, and the planes of cleavage which account for the material's amazing lubricity. (The Alpha Molykote Corp., LE-11/4, 65 Harvard Ave., Stamford, Conn.)

Viscosity Chart. Metal mounted with plactic front, a "Minimum & Maximum Viscosities for Varying Viscosity Indices" chart has been made available showing at a glance the maximum and mini-

(Men of Lubrication, from Page 229)

mental faculties were not impaired as he grew older and he was active in science to the end.

ACKNOWLEDGEMENT. The main sources consulted in the preparation of this article have been the memorials "Arnold Sommerfeld: 1868-1951," by Linus Pauling (Science, Oct. 12, 1951), and "Arnold Sommerfeld," by Von W. Heisenberg (Die Naturwissenchaften, August 1951); also current "Biographies 1950," and the Foreword to "Sommerfeld's Mechanics," by P. P. Ewald.

(Lube Lines, from Page 213)

$275,000 research program), Supervisor of Fluid Mechanics in the Foundation's Heat-Power Research Dept., emphasizes that "hot boxes result from a combination of unfavorable conditions rather than a single isolated factor." With this in mind, he recommends that a number of actions be taken to improve journal bearing performance in railroad service: (1) Obtain improved fit of the bearing on the journal; (2) Eliminate or greatly reduce the friction heat produced by the waste pack in the oil wick system which provides lubricating oil for the journal; (3) Obtain improved cooling of the journal box; (4) Utilize an oil having greater viscosity at high temperatures than oils now used. As part of the research project, the Foundation's Chemistry & Chemical Engineering Research Dept. conducted a study of oil additives which resulted in the development of improved additives for reducing friction on the bearing under incipient hot box conditions. The department's investigation indicates that additives of the fatty acid type, especially oleic acid, provide the greatest friction reduction.

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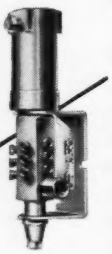

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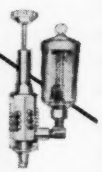
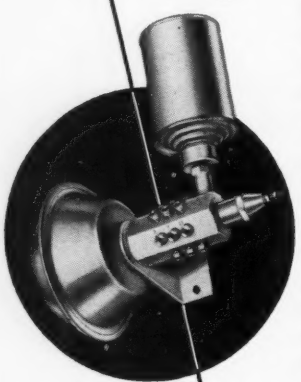
Adopted by leading Fleet and Bus Operators for automatic, controlled lubricant application each time driver applies the air brake. Complete Systems available in handy kits for simple installation. Air-Operated Multi-Luber Systems may be used wherever compressed air is available to reduce operating costs and increase efficiency on equipment ranging from transport trailers to automated, high speed lathes.



Where compressed air is not available, the air cylinder of the Multi-Luber can be replaced with a push button. These Manual Systems are available in kits for quick installation on tractors, farm implements, and a wide range of industrial machinery.



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mum viscosities for lubricating oils graded from SAE 5W to SAE 50, and covering all viscosity indices from 0 to 120. Readings are given in Centistokes, Redwood Seconds, Saybolt Universal Seconds, and Engler Degrees. (Scientific Publications, Ltd., LE-11/4, Broseley, Shropshire, England; price $5.00 postpaid).

Honan-Crane Oil Filters. Three new bulletins have been released that tell the full story of Houdaille-Hershey's new line of Honan-Crane oil filters. In addition to the engineering features of each filter, they cover specifications, typical applications, details of operation, and filter media data. Bulletin 101 describes the Full-Flow Filter (available in 9 different sizes) designed for in-line installation, and offering operators flow rates of up to 900 gpm at very low pressure drops. Bulletin 201 describes the Multi-Cartridge Filter in which 6 different types of cartridge elements can be used interchangeably; by switching from one type cartridge to another, operators can get the exact degree of filtration needed for virtually any industrial oil or coolant. Bulletin 301 covers Bulk-Type Filters which provide depth-type filtration and are used in applications where oil must be kept absolutely clean. (Houdaille-Hershey of Indiana, Inc., LE-11/4, 20 S. Ave., Lebanon, Ind.)

Silicone Defoamers. Properties and performance of Dow Corning silicone defoamers are detailed in a new brochure, with special attention given to Antifoam AF Emulsion (said to be the most efficient, versatile, and easiest-to-disperse foam killer on the market) and its parent material, the original Antifoam A Compound. Suggested concentrations, dispersing media, and application methods are discussed, along with actual working examples in fields ranging from food processing to metal-working. (Dow Corning Corp., LE-11/4, Midland, Mich.)

Triple Service Lubricator. Technical Reference 55A describes and

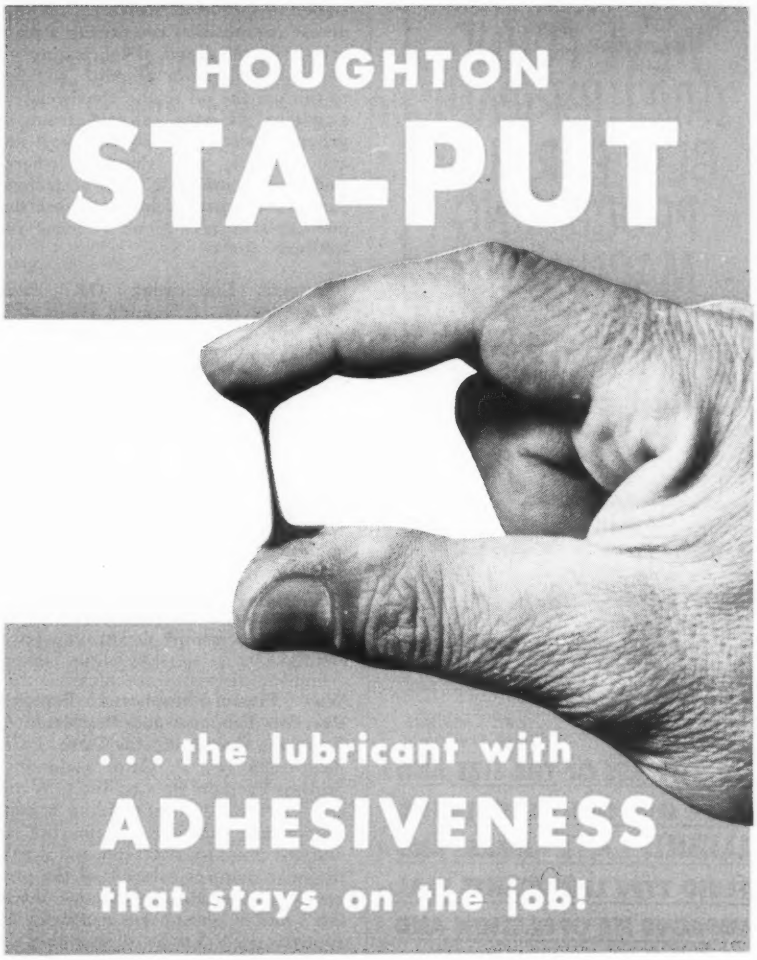
illustrates a triple service automatic lubricator that provides continuous, jetting, and cyclic types of lubrication from a single compact unit. Only 9¾" high, this lubricator is particularly adaptable for machinery which require a variety of oiling methods to varying mechanical motions. The bulletin includes a large labeled flow diagram of the system, illustrating the normal flow of oil through the entire lubricator system as well as the operation of jetting (or intermittent), continuous (low-pressure), and cyclic (high-pressure) oiling branches. (Bijur Lubricating Corp., LE-11 /4, 151 W. Passaic, Rochelle Park, N. J.)

(Patent Abstracts, from Page 273)

Lubricating Greases Containing an Acidic Copolymer Salt, Patent #2,698,298 (J. J. Giammaria, assignor to Socony-Vacuum Oil Co., Inc.) A grease comprising a mineral lubricating oil fraction and a salt in an amount sufficient to thicken said oil fraction to form a grease, said salt being a salt of an acidic copolymer of an aliphatic compound having a terminal vinyl group and an alkyl radical having from ten to thirty carbon atoms and an alpha beta unsaturated polycarboxylic acid, the metal of said salt being selected from the group consisting of metals of groups I, II and III of the periodic system, and said acidic copolymer having a molecular weight of about 1000 to about 2000.

Modified Acidic Copolymer-Fatty Acid Soap Greases, Patent #2,698,299 (J. J. Giammaria, assignor to Socony-Vacuum Oil Co., Inc.) A modified grease comprising a major proportion of a lubricating oleaginous vehicle, a minor proportion of a mixed gelling agent and an amount of an aliphatic monocarboxylic acid having less than six carbon atoms and a molar equivalent of a metal of group II of the periodic system sufficient to provide a grease having a dropping point of at least 300 F., said gelling agent comprising a mixture of salts of a metal of group II of the periodic system and (1) an acidic copolymer of an alpha beta unsaturated polycarboxylic acid and an aliphatic compound having a terminal vinyl group, said acidic copolymer having a molecular weight of about 1000 to about 2000, and (2) a saturated aliphatic monocarboxylic acid having 10 to 22 carbon atoms.

Greases Thickened with Acyl Ureas, Patent #2,698,300 (B. W. Hotten, as-



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signor to California Research Corp.) A grease composition comprising a major proportion of an oil of lubricating viscosity and a minor amount, sufficient to thicken the oil to the consistency of a grease, of urea selected from the group consisting of aliphatic acyl urea and aliphatic acyl thiourea, wherein said urea contains a total of from 11 to 27 carbon atoms and not more than one aliphatic acyl group attached to a nitrogen atom.

Synthetic Lubricating Oil, Patent #2,698,324 (A. J. Shmidl, assignor, by mesne assignments, to Standard Oil Development Co.) An oxidation resistant lubricating oil composition which is the product formed by reacting within the range of 2 to 4 parts of monocyclic alkyl naphthene in the boiling range of 80 to 430 F. with one part of alpha olefin within the range of C_5 to C_{18} and phenothiazine within the range of .1 to 1 weight per cent based on said alpha olefin in the presence of a Friedel-Crafts type of catalyst within the range of 1 to 5% based on said alpha olefin with the temperature of the reaction within the range of 0 to 250 F.

Wax Phenol-Phosphorus Pentoxide Reaction Products and Petroleum Oil Fractions Containing the Same, Patent #2,698,835 (F. P. Otto, assignor to Socony-Vacuum Oil Co., Inc.) A mineral lubricating oil containing a minor proportion, sufficient to improve the extreme pressure character and depress the pour point of said oil, of the product obtained from the reaction involving 1 mol of phosphorus pentoxide and approximately 3 mols of wax phenol at a temperature of from about 50 C. to about 150 C.

Lubricating Oil Composition, Patent #2,699,429 (W. Lowenstein-Lom, assignor to Standard Oil Development Co.) A lubricating oil composition consisting essentially of a mineral lubricating oil containing dissolved therein about 2% by weight, based on total composition, of isopropyl oleate and about 2% by weight, based on total composition, of tributyl phosphate.

Surface-Active Compounds and Fuel Compositions Containing Them, Patent #2,699,991 (R. D. Stayner & R. A. Stayner, assignors to California Research Corp.) A hydrocarbon oil composition containing a small amount sufficient to inhibit line and filter clogging and corrosion of a member of the group consisting of 2-[N,N-di-(alkylbenzyl)-N-methyl ammonium]-ethyl sulfates and 2-[N-alkylbenzyl-N, N-dimethyl ammonium]-ethyl sulfates having a long chain alkyl substituent of from 9 to 18 carbon atoms on the benzene nucleus.

Sugar Ester-Containing Lubricant Compositions, Patent #2,700,022 (J. O. Clayton, E. G. Lindstrom, & F. A. Stuart, assignors to California Research Corp.) A gasoline engine crankcase lubricant composition comprising a major portion of a substantially wax-free oil of lubricating viscosity and a total of from about 4 to 10% by weight of a saccharide selected from the group consisting of pentoses, hexoses and sucrose in which at least one hydroxyl group is esterfied with an aliphatic carboxylic acid having at least 10 carbon atoms in the molecule, said lubricant composition having the ability to effectively inhibit the formation of deleterious deposits in gasoline engines operated at the relatively low temperatures of city driving conditions.

Process of Bonding Solid Lubricant to a Metal Surface, Patent #2,700,623 (R. D. Hall, assignor to Electrofilm, Inc.) A process for bonding solid lubricant to a non-ferrous metal friction surface which comprises applying thereto a thin coating of indium or an alloy thereof, heating said surface to bond said coating thereto by diffusion, applying to said coated surface finely divided solid lubricant suspended in an organic vehicle comprising a solution of an organic resin, allowing said second coating to air dry, and heating the coated surface to a temperature above the melting point of the coating metal to embed solid lubricant therein.

Process for the Production of a High Quality Lube Oil, Patent #2,701,783 (R. B. Long & W. M. Basch, assignors to Standard Oil Development Co.) Process for the production of a high quality lubricating oil product having a low neutralization number from a feed oil having a relatively high neutralization number which comprises contacting said feed oil with a solvent having a preferential selectivity for the more aromatic type constituents as compared to the more paraffinic type constituents and using in conjunction with said solvent from about 0.2 to 0.4 volume percent of ammonia based upon the amount of feed oil, separating a raffinate phase and recovering said high quality lubricating oil product therefrom.

Synthetic Lubricants, Patent #2,701,803 (B. A. Orkin, assignor to Socony-Vacuum Oil Co., Inc.) A compound having the formula $R_nSi(TR')_{4-n}$ wherein R and R' are radicals selected from the group consisting of alkyl, thienyl and benzyl radicals, T is a divalent atom selected from the group consisting of oxygen and sulfur atoms, and n is an integer varying between one and three, in which the total number of carbon atoms plus heterocyclic atoms in each molecule varies between 26 atoms and 38 atoms, there being not more than 3 heter-cyclic atoms per molecule, and in which at least one of said radicals R and R' is an alkyl radical; said compound being a lubricant having a relatively low pour point, a high viscosity index, a viscosity in the lubricating oil range, and resistance to hydrolysis.

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Ind. Mgmt. Engr. (261-LE) MBA-ME; 6 yrs. plt. surveys, financial & operations analysis; 1 yr. supv. time studies & method engr. on steel rolling; 7 yrs. genl. industrial consulting on eqpt., tooling, systems, procedures & mgmt. controls; Midwest; $9,000.

Ind. Mgmt. Engr. (262-LE) 28, MS Adm. Engrg.; 6 yrs. resp. for adm. of Ind. Engrg. activities in prod. dept. of printing plant; 1 yr. resp. for engrg. design of timber structures; Chicago, $8,000.

Constr. Supt. (263-LE) 37; 2 yrs. electrical estm. on power station & sub station eqpt. & cable estims.; 2 yrs. layout & design of power & light; 1 yr. estimator-draftsman for constr. co.; 1 yr. layout of reinforced concrete bldgs.; Chicago, $6,000.

Petroleum Engr. (264-LE) 28, ME; 3½ yrs. designing pumping stations, analyzing quotes on eqpt., hydraulic computations, economic studies; 1 yr. plt. maint.; 1 yr. on drafting board; Midwest, $5,500.

Ch. Ind. Engr. (265-LE) 36; 1 yr. installation of methods & wage incentive program; 6 yrs. charge of wage incentives, plant layout, job evaluation, costs, time & methods study; knowledge of plastics, electronics & sheet metal; Chicago; $6,500.

Staff Engr. (266-LE) 34, ME; 2 yrs. plant layout, layout of process eqpt., sewer lines & ventilating systems; 7 yrs. design of material handling & new ordnance eqpt.; Chicago; $7,000.

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C-2905, Maint. Engrs. (2). Grad. Mech.; age to 35; 2 plus yrs. exp. pref. in plant maint. or design in process industry; duties: work in plant maintenance div. of process plant checking machinery, installation of eqpt. & preventive maint.; plant employs 3,000; very modern eqpt., mostly automatic machine operations; good oppor. to move into project engrg. or master mechanic over 4 plants; salary $6,500; location, SW side of Chicago.

C-2908, Sales — Ind. Lubricants. Prev. industrial sales preferred; knowledge of mach. tools; duties: selling line of industrial lubricants to manufacturers; for a petroleum refinery; sal. $350-425; loc., Ohio or Mich.

C-2921, Tech. Corresp. Age 25-28, 55-68; 2 plus yrs. exp. in writing reports or technical work on chemical or water treating; knowledge of boilers, coolers & air conditioning; duties: writing tech. reports to men in the field covering information on boilers, coolers, air conditioning & other phases of using & treating water; for a mfger. of water treatment; sal. $350-500; employer will pay fee; loc. Chicago.

C-2958, Const. Supt. Grad. CE; age to 45; 6 plus yrs. exp. in heavy type of construction; exp. in const. costs; knowledge of chemical or oil industries desirable; duties: supervise const. of heavy plate work, tanks, foundations, etc., for chemical & oil refinery const. assignments all over country; usual duration of job about 6 months; sal. $8-10,000 plus incentive; loc. Hqs. Chicago.

C-2959, Designer — Process. Mech. or Chem.; 3 plus yrs. exp. in chemical process eqpt. design; company will pay moving expenses; sal. up to $7,200; loc. Tex., population 12,000, housing conditions fair.

C2963, Sales Trainee. Chem. Eng.; age 26-30; 2 plus yrs. exp. in sales or work allied to sales; knowledge of water treating helpful; duties: estimating or internal sales work for manufacturers of water treating eqpt. as sales trainee; training period for 2 yrs. & then assigned to a territory as a sales man; sal. $4,500-5,500; employer wil. negotiate fee; loc. NY (will be assigned to territory later).

C-2966, Project Engr. BS ME; age 25-35; 2 yrs. exp. project engrg. assignments in related fields; knowledge of testing, developing or designing mech. apparatus; duties: resp. for tech. direction of individual development projects on improvement of dry clutch & aircraft brake friction facings; sal. $6-700; employer will negotiate fee; loc. Ohio.

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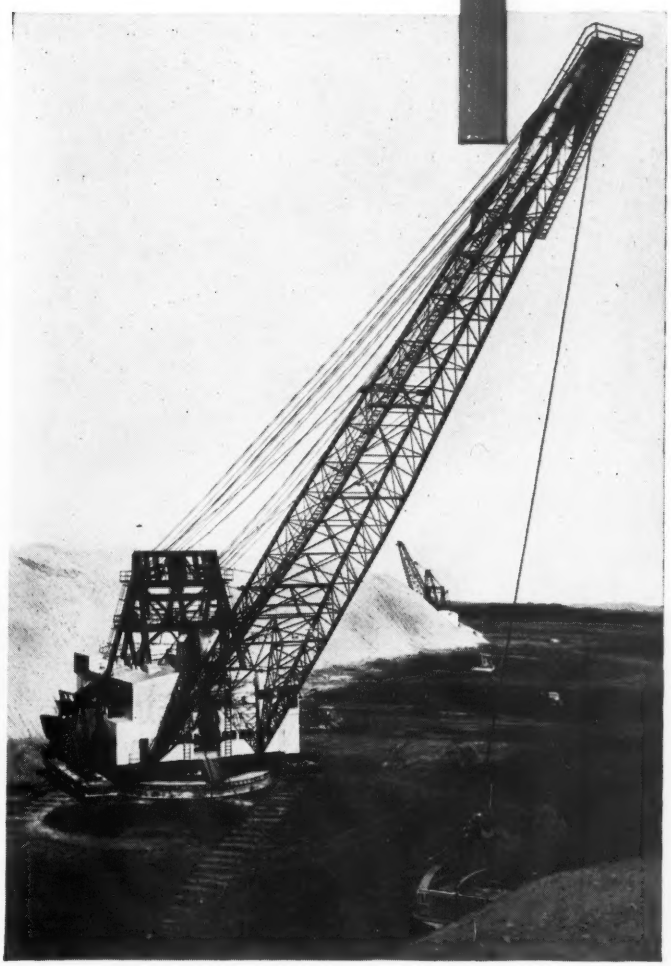

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